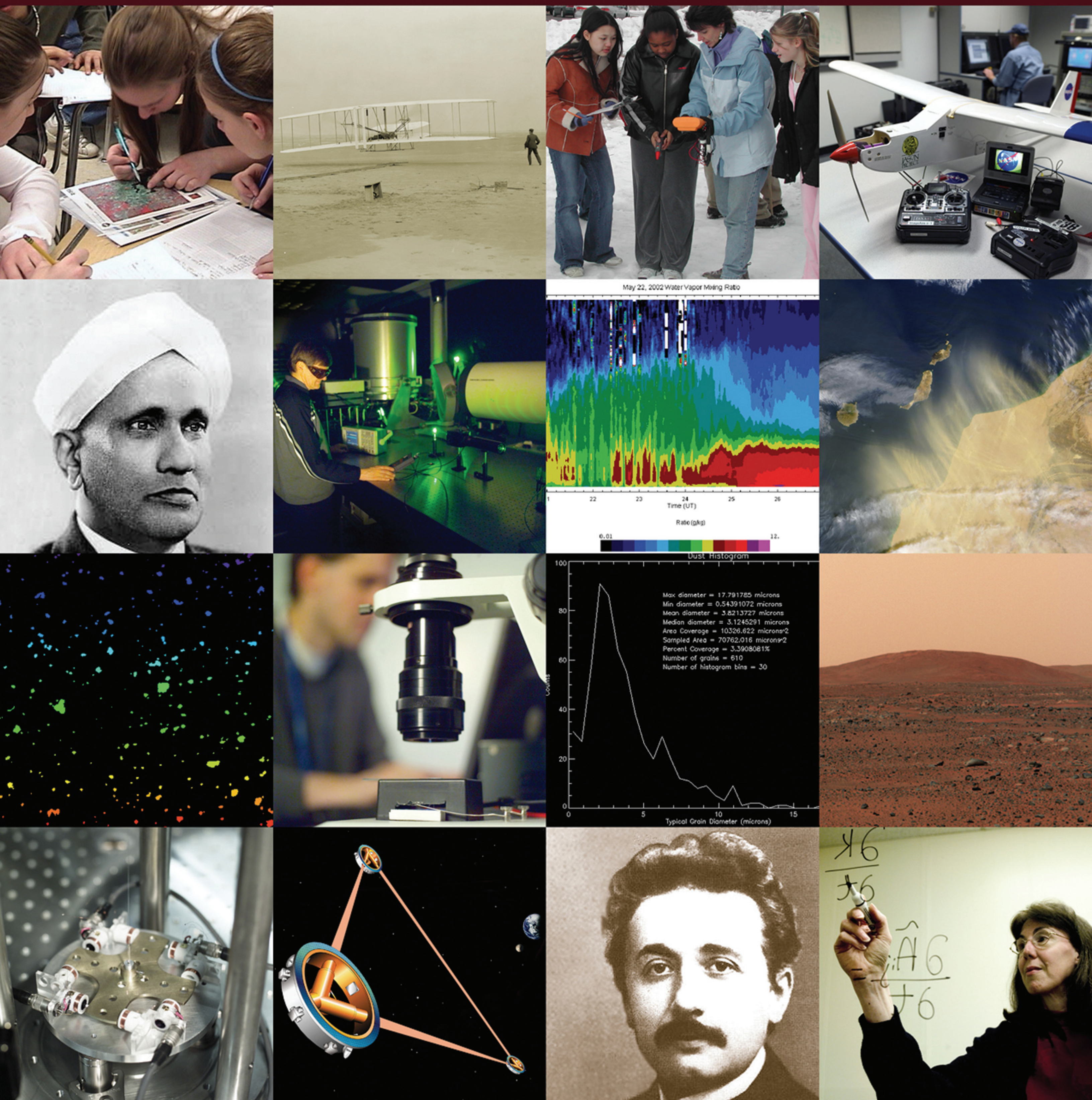
2003

Goddard Space Flight Center

Director's Discretionary Fund Annual Report



About the Cover

The four lines of photographs on the cover represent four reports featured in the annual summary this year.

Line 1: Possibly the Wright brothers envisioned remotely controlled aircraft and would have enjoyed watching students outfitting UAVs with instruments (see page 127).

Line 2: It may well have occurred to Chandrasekhara Raman that his work on scattering of light from molecules could be used to diagnose the properties of particles suspended in air (see page 91).

Line 3: Dust is everywhere, and differs from place to place. Martian dust can tell much about the history of Mars, but the characterization of the dust will require specialized tools such as the robotic instrument whose development is depicted here (see page 3).

Line 4: A young Albert Einstein's insight into space and time led to the expectation of gravitational waves from such sources as distant, colliding black holes. Detecting them with the LISA constellation of satellites will require acceleration noise testing with exquisite torsion pendulum fibers like the one shown here (see page 49).

PREFACE

Director's Discretionary Funds (DDF) are used at Goddard to encourage potentially important exploratory research projects. The emphasis is on a high degree of innovation, high payoff to Goddard and NASA if successful, and higher than usual technical risk. About 10% of the funds are used for innovative education projects. We began including Education some time ago, but now that it is a NASA Enterprise its inclusion is especially important.

Projects are recommended to me by the Goddard Senior Fellows, about two dozen of our best minds in science and engineering. Fewer than one out of three proposals are recommended. Many more are worthwhile, but increasingly, in recent decades, the science we are ready and eager to do is increasing much faster than funds to do it.

The individual project reports are collected in four sections: Engineering, Space Science, Earth Science, and Education. Each follows the format mandated in recent years with one addition--that of a "Key Points Summary" which lists innovative features, payoff to Goddard and NASA, criteria for project success, and risk factors. We asked the Senior Fellows and Bob Gabrys, the Goddard Education Officer, for advice on examples of the best proposals in each section. Each of the four sections begins with one such example. For all reports, we have tried to ensure that the opening paragraph of Purpose of Investigation as well as Key Points Summary can be read and enjoyed by those not necessarily familiar with the type of work reported.

The examples introducing the four sections are:

• ***Engineering.*** This project developed equipment and techniques for robotic Mars exploration around the end of the decade to collect and to characterize dust on Mars. Since there is minimal or no weather on Mars, its dust can reveal important information on the Martian geologic processes that produced the dust over the last few billion years. We have learned a lot about Martian dust from scattering and absorption of light from stars as Mars is just starting to pass between us and the star, as well as from the probes that have orbited, and landed on, Mars. With the results of this project, we will be able to study the dust up close and personal. [*Development of a Martian Dust Characterization Instrument*]

•***Space Science.*** The three satellite Laser Interferometric Space Antenna (LISA) observatory will detect gravitational waves by tracking changes in distance among "proof masses" floating inside each satellite. An essential feature of the mission is a feedback control system to keep each satellite (buffeted by small, random forces) from disturbing its contained proof mass; the requirement is to keep the proof mass from accelerating more than a tenth of a trillionth of a centimeter per second per second over a thousand second period. This feedback system will be tested with a space test mission before LISA is launched in the next decade. The DDF project is to enable testing of the feedback system on the ground before the test mission. The testing will be done with a torsion pendulum, a device extremely sensitive to external forces. The DDF project investigates an innovation to current torsion pendulum designs, which could result in a factor of 100 higher sensitivity. This would allow ground testing of the satellite control system at the full LISA requirements before the space missions. [*Development of Fused Silica Fibers for use in LISA Torsion Pendulum Apparatus*]

•***Earth Science.*** Aerosols (particles suspended in the atmosphere) are transformed into cloud droplets by processes not yet well understood. A new technique is showing the feasibility of using "multi-wavelength Raman Lidar" (a laser beam of one wavelength goes out and several wavelengths are returned) to measure properties of the aerosols and those of the clouds simultaneously. This technique should permit studying directly, rather than inferring indirectly, transformation of an aerosol into a cloud droplet. [*New Lidar Technique for Measuring the Direct and Indirect Effects of Aerosols*]

•***Education.*** A model UAV (Unpiloted Air Vehicle) program and UAV/Satellite Remote Sensing curriculum module demonstrates how students, teachers, scientists and model airplane clubs can partner to put Earth Science sensors in small, remotely-piloted aircraft to collect instructive NASA Earth Science data. This should, for the students, add excitement to learning how to collect and analyze data while, for club members, add public service to enjoying model airplanes. It takes science out of the textbook and into the field. [*A Model Plan to Share UAV Technologies with Educational Communities*]

I think the reader will find these, and others in this volume, to be high-payoff, exciting, innovative projects.

Finally, I want to thank the Goddard Senior Fellows for selecting recommended projects and helping evaluate the reports; Code 660's Christopher Wanjek, Pat Tyler, and Irene Stone for editing and layout; Chris Gunn for the cover; and all the DDF recipients for good ideas and hard work.

A. V. Diaz

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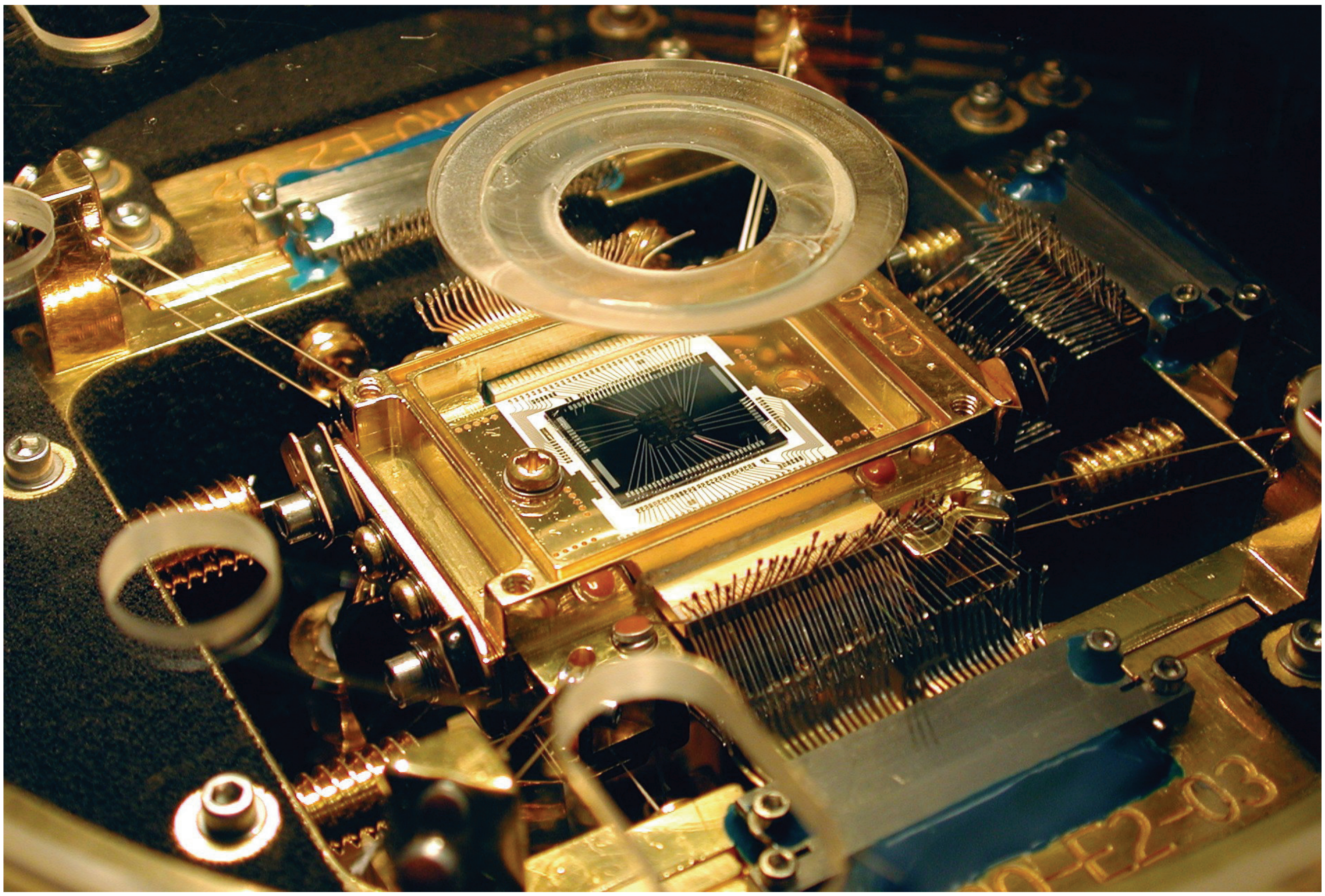
Applied Engineering



and Technology Directorate

Development of a Martian Dust Characterization Instrument

Principal Investigator: Brent J. Bos (Code 551)

Co-Investigators: Peter H. Smith (University of Arizona), Nilton Renno (University of Michigan), Robert Zubrin (International Mars Society)

Initiation Year: 2003

FY 2003 Authorized Funding: $13,000

Actual or Expected Expenditure of FY 2003 Funding: $13,000 for microscope optics and off-the-shelf detectors

Status of Investigation at End of FY 2003: To be continued in FY 2004 with funds remaining from FY 2003

Expected Completion Date: August 31, 2004

Purpose of Investigation:

This research will enable dust sampling on Mars by bringing the current Martian dust characterization instrument development to a Technology Readiness Level (TRL) 3, a proof of concept stage, the third of nine levels. Martian dust samples provide information about the Martian atmosphere, including how hot the planet can get and how carbon dioxide "ice" gets deposited at the polar regions by dust. We are testing the current laboratory approach of imaging dust particles with a high-resolution video microscope, at about 1-micron resolution, by bringing the instruments to the field -- that is, to two deserts in the United States with dusty conditions similar to those of Mars. We aim to test and develop advanced dust-image-processing algorithms using our field data. We also aim to provide important dust characteristics data for Goddard's ground-based and Mars-based analog dust research projects in Code 695. With this, we plan to develop field-tested instrument-design guidelines for future robotic Mars missions planned for 2007 and 2009. Also, we are studying how the adhesion properties of dust collectors affect the dust size distribution measured.

Accomplishments to Date:

Due to the late initiation of DDF funding and the purchasing blackout period at Goddard, this project is approximately six months behind schedule. The majority of the remaining work is in the field data reduction and analysis. A portable, digital-imaging, dust microscopy system was designed and assembled from commercially available modular components. Its primary purpose is to facilitate measuring the size and shapes of particles about 2 microns and larger, and to generate dust size statistics.

Mars analogue fieldwork was conducted at two locations, both U.S. deserts: near Hanksville, Utah, at the International Mars Society's Mars Desert Research Station, or MDRS; and near Eloy, Arizona, at the University of Arizona Lunar and Planetary Laboratory. The MDRS in Utah was used as an initial test bed to work out instrument and software bugs before dust devil research in Arizona. Dust traps, consisting of glass microscope slides and wind barriers, were deposited at various locations around the MDRS for varying durations. Samples were then gathered and imaged to generate ambient dust fall data and to evaluate instrument design.

Initially, dark-field illumination (image bright against dark background) was intended to generate high-contrast dust images, but during the course of the MDRS fieldwork we found bright-field illumination to be significantly superior. Bright, specular reflections off dust particles and the lack of dust edge contrast were the two primary disadvantages of dark-field illumination -- that is, beside the inherent inefficiency of this illumination geometry. Figure 1 is an example of a bright-field illumination dust image with a human hair included for scale.

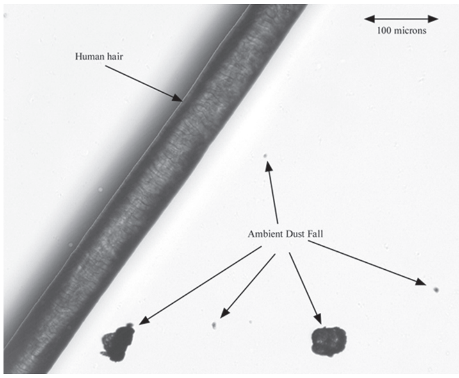


Figure 1. Microscope bright-field illumination image of dust particles with a human hair included for scale.

Scientifically, the Arizona fieldwork was of most interest. The goal was to measure naturally occurring terrestrial dust devils to prepare for studying significantly larger, phenomena on Mars. Peter Smith of the University of Arizona and Bill Farrell of Goddard initiated this field campaign in 2001 under the Matador moniker. It was the subject of a Discover magazine article in July 2003. Our dust traps were carried by the dust devil chase vehicle for direct sampling of dust devil material. From approximately 10:00 am to 2:00 pm local time, almost constant dust devil activity was observed at the Arizona field site from June 2-4, 2003. Some dust devils were short-lived while others lasted for several minutes. We obtained dust samples from five dust devils. Figure 2 shows the large dust devil intercepted on June 3 in infancy on the right and at full strength on the left.

Figure 2. Large dust devil intercepted on June 3, 2003.

The instrument itself was not placed in the path of the dust devils. Glass microscope slides with various adhesive properties were mounted on a deployable boom to collect from within the devils for later imaging. Reduction of the images into dust size, shape and size distribution data is ongoing with custom Interactive Data Language (IDL) programs to generate particle size and shape data. Measurements define the lengths of the sides of the smallest rectangle that could be drawn around the 2-dimensional projection of the particle. Finally, a particle shape factor is calculated by dividing the second length measurement by the first. Examples of information extracted are shown in Figures 3 and 4.

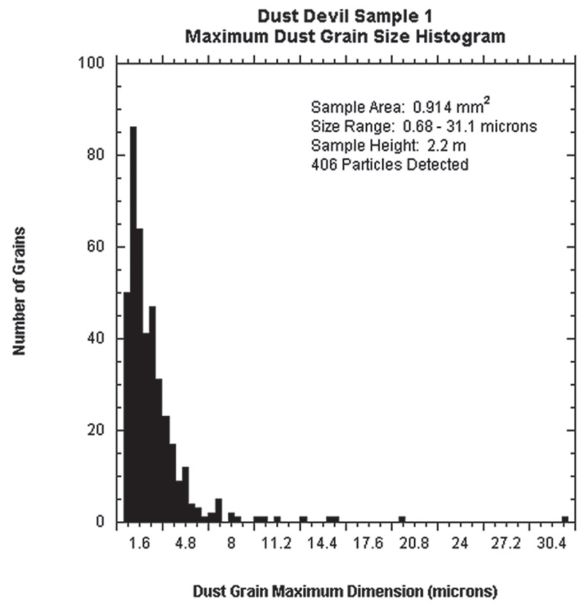


Figure 3. Dust particle maximum size distribution data from the first dust devil intercepted on June 2, 2003.

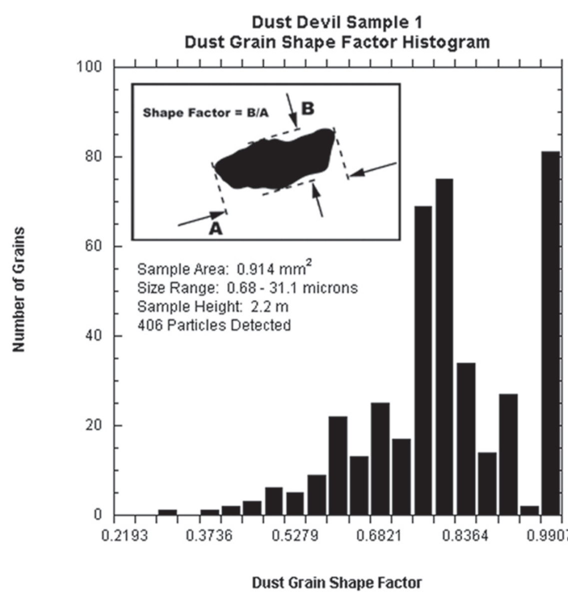


Figure 4. Dust particle shape factor distribution data from the first dust devil intercepted on June 2, 2003, the figure insert illustrates the shape factor definition.

Figure 3 is a histogram of dust particle lengths from the first dust devil. Notice how the particle count in the first non-zero bin, representing lengths of 0.457-0.914 μm, is less than one would physically expect. This is due to instrument resolution cut-off of 0.9640 μm. Figure 4 is a histogram of the shape factor measurements for the particles shown in Figure 3. There are two interesting features. First, the largest bin represents a shape factor of 1.0, which would indicate that the two-dimensional projection of those particles is rotationally symmetric. But within that bin are 51 particles that were unresolvable by the instrument, and so the results are misleading. If those particles are removed, the count for that bin is reduced to 30. With that effect taken into account, the peak of the shape factor distribution occurs at values 0.740-0.817, representing 35% of the sample. This is consistent with the shape factors for desert sand of 0.75. Second, the extremely low shape factors measured, below 0.4, are probably due to biologically created particles and not from the soil-derived dust of primary interest in this study.

Although and data analysis is ongoing, we have some important conclusions regarding instruments for dust characterization on Mars landers. To measure ambient dust fall, an automated device similar in design to the instrument for this study would be ideal (figure 5). Such an instrument would include a telecentric optical microscope with a bright field illumination system. A transparent, motorized turntable would be required to bring dust samples into the microscope's field of view after being exposed to the Martian atmosphere. Our fieldwork stressed the fact that high image resolution is always advantageous. And so the instrument resolution should be as high as possible for an optical instrument. With custom optics this would be about 0.5 μm, about twice the resolution of the off-the-shelf assembly built for this study. Since the instrument design would include a moveable sample platform, the microscope would not have to be a zoom system. To sample larger areas than the high-magnification, instantaneous field of view would allow, the dust turntable would be rotated to obtain images at different turntable positions.

Second, an instrument designed for measuring ambient dust fall is not ideal for measuring dynamic dust particles in a Martian dust devil. Such an instrument, as described in the previous paragraph, requires some method of dust trapping or capture in order to make a measurement. And although our dust devil data analysis continues, we have observed that dust trap orientation and adhesion properties greatly affect the dust distribution measured in the dust vortex. We have begun exploring possible instrument designs for in-situ measurements of dust particles trapped in dust devils.

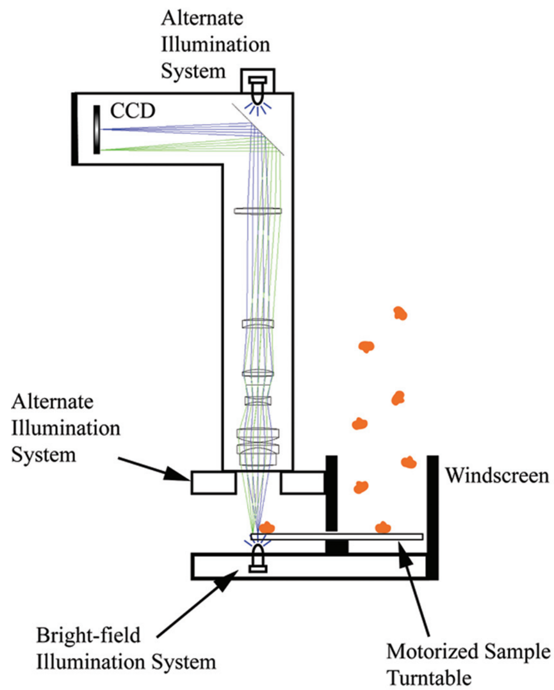


Figure 5. Diagram of an optimized ambient dust fall characterization instrument.

Planned Future Work:

Dust data reduction and analysis will continue into mid-2004. This will include investigating the functional fit that best represents the data. Results will be submitted for publication. Our work has generated two new research areas we will pursue in 2004. The first will be to determine Martian dust properties from Imager for Mars Pathfinder (IMP) dust-contaminated images. During the Mars Pathfinder mission, dust came to rest on the IMP exterior windows. The particle images are out of focus, but it will be possible to use image-processing techniques to calculate dust size and shape. We have submitted a proposal with co-investigator Nilton Renno of the University of Michigan Space Physics Research Laboratory in response to a NASA Research Announcement.

The second research area will be to generate and test, in the field, a design for dynamically measuring dust devil particle characteristics non-intrusively rather than by trapping. We know three types of designs for an optical instrument to generate dust size and distribution data without trapping. All would observe dust particles as they travel past the instrument without capturing them. Besides dust particle size, such an instrument would be capable of measuring particle velocity as well.

Summary:

The most innovative aspect of this work was actually field-testing a proposed Martian dust characterization instrument. Testing an instrument in the field -- making the same types of measurements that we ultimately want to make on Mars -- is the best method for determining an instrument's strengths and weaknesses. The lessons learned ultimately will produce better instruments for NASA Mars lander missions, higher-quality data for the scientific community, and increase Goddard's standards in this field. We have met our criteria of success in that we developed a fuller picture of dust-size distribution in the field during a naturally occurring dust devil, a miniature whirlwind that whips up dust in the air. We have also increased interaction with researchers at the University of Michigan, University of Arizona and the Mars Society. We are currently in discussion with the University of Arizona to offer support to the 2007 Phoenix Mars Scout mission.

Cryogenic High-Accuracy Refraction Measuring System (CHARMS)

Principle Investigator: Bradley Frey (code 551)

Other Investigators: Douglas Leviton (code 551)

Initiation Year: FY 2003

Funding Authorized for FY 2003: $52,000

Actual or Expected Expenditure of FY 2003 Funding: Mechanical spin tables, $10,000; Temperature sensors and monitor, $6,000; Vacuum and cryogen hardware, $5,000 Minco Heaters and power supplies, $5,000 ; LN2 shrouds, $4,000; Optics and mounts $4,000; Contractor support, $18,000 (expected)

Status of Investigation at End of FY 2003: To be continued in FY 2004 with funds remaining from FY03, then transition to funding from JWST/NIRCam

Expected Completion Date: Summer 2004

Purpose of Investigation:

The purpose of this investigation is to construct a facility at Goddard to measure the index of refraction of a wide variety of optical materials at their design operating temperatures and wavelengths. The index of refraction is a property intrinsic to a material and describes how much the path of light passing through that material is bent. Not only is the index of refraction different from one material to another, but for any given material it also changes as the temperature and wavelength ("color" of the light) change. Accurate knowledge of this change is important when an instrument is designed and built on the ground, but then expected to operate in space or at a variety of wavelengths to achieve interesting science goals.

CHARMS will measure refractive index using the minimum-deviation method and will be capable of performing these measurements at wavelengths ranging from the infrared through the far-ultraviolet and at temperatures from 10K to 100°C. We anticipate CHARMS will be able to measure the index of refraction *to an accuracy of five decimal places*. Because of the inherent difficulty (including expense) and complexity in making these measurements, the refractive index has not previously been measured to this accuracy; without CHARMS we could not otherwise meet the requirements of many upcoming NASA missions.

The focus of this DDF project is to develop the various ultrahigh-accuracy metrology tools that still work well under extreme temperature conditions necessary to achieve our desired measurement accuracy; to design and fabricate a thermal system capable of cooling our sample material to the desired cryogenic temperatures; and then to assemble, test, and characterize the refractometer system as a whole.

Accomplishments to Date:

To measure refractive index we use the method of minimum-deviation refractometry. This method is extremely challenging in that it requires very accurate knowledge of two angles: (1) the deviation angle of the beam passing through the sample under the condition of minimum deviation, and (2) the apex angle of our sample prism, both as a function of temperature. The condition of minimum deviation is established when the incident angle of an incoming (incident) ray is equal to that of the outgoing (deviated) ray; consequently, inside the prism the ray propagates perpendicular to the bisector of the apex. The difference between the direction of the undeviated ray and the direction of the deviated ray is the "deviation angle" through the prism.

Our current opto-mechanical layout is pictured in figure 1. To measure the deviated and undeviated ray angles, we have used a rotary version of the Leviton absolute optical encoder, which was successfully developed under previous GSFC/DDF funding. These optical encoders are located on both the sample prism stage and the rotating fold mirror stage in figure 1.

Based on the success of the original optical encoders, we have modified the design for CHARMS to include a 50K fiber image conduit to allow us to use the encoder in our cryogenic environment. The cryostatically capable version of the encoder "read" station and electronics are pictured in figure 2. These encoders allow us to measure the necessary

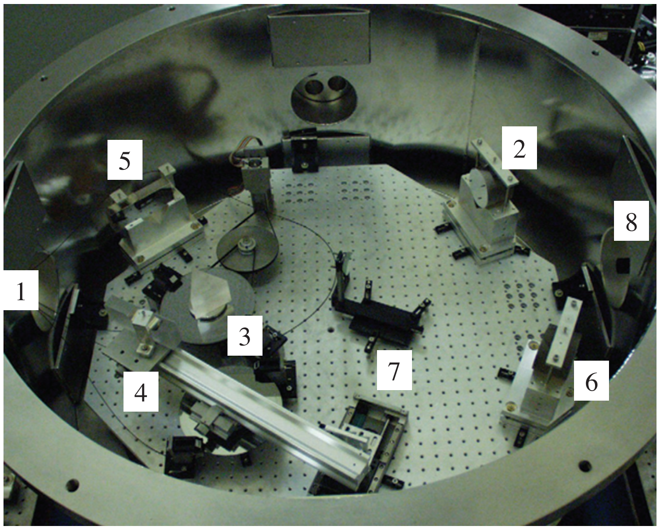
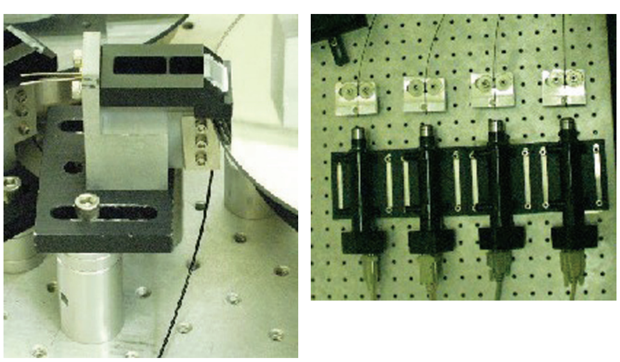


Figure 1: Current layout of CHARMS: (1) source (not shown), (2) collimating mirror, (3) sample prism and rotary stage, (4) rotating fold mirror, (5) fixed fold mirror, (6) camera mirror, (7) focus mirror, (8) detector (not shown).

rotation angles to an absolute accuracy of ±0.1 arcseconds.

To measure the apex angle of our sample prism, we have developed another derivative of the Leviton absolute optical encoder -- this time a new application of the Cartesian scale pattern. Building on the already proven technology in the absolute Cartesian encoder, we have developed an electronic Cartesian autocollimator (CAC) that allows us to measure the apex angle of our sample prism, even at cryogenic temperatures, to ±0.5 arcseconds. An implementation of the CAC similar to what we will be using in CHARMS is pictured in figure 3.



(a) (b)

Figure 2: Leviton absolute optical encoders: (2a) Encoder read head with 50K fiber image conduit. (2b) Encoder electronics located external to thermal vacuum chamber.

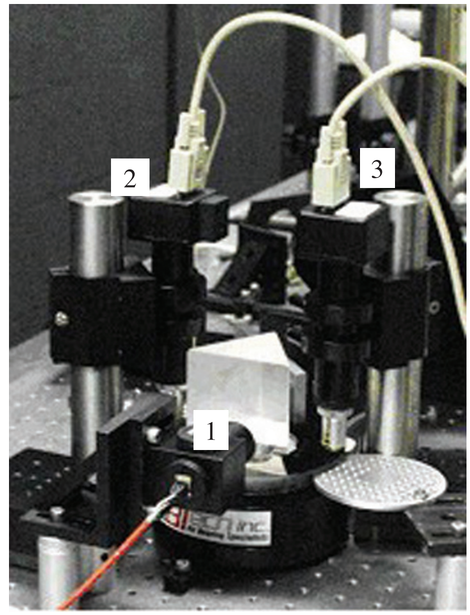


Figure 3: Laboratory setup to measure sample prism apex angle using (1) short focal length (60mm) CAC, and (2), (3) rotary implementation of Leviton absolute optical encoders; this setup is analogous to what will be built into CHARMS.

To verify our measurement capabilities to date, we measured the index of refraction of a fused silica prism in the visible with a nominal apex angle of 60° under ambient conditions (1 atm, 25° C) and compared our measured values with measurements made by I.H. Malitson in the 1960s at the National Bureau of Standards (see figure 4). Our overall measurement accuracy for this configuration is $\pm 1 x 10^{-5}$ (typical for visible measurements). Typical accuracies will vary by material and wavelength, but we expect to achieve results accurate to better than $\pm 5 x 10^{-5}$ in both the infrared and ultraviolet.

Finally, we have presented and published three CHARMS related papers over the past year at two different Society of Photo-optical Instrumentation Engineers (SPIE) conferences. In addition, we have plans to present two additional CHARMS papers at next year's SPIE conference.

Planned Future Work:

We plan to continue our current work with our existing funding as we improve the capabilities of CHARMS. We have made measurements in the visible at ambient conditions, and are currently testing the thermal system and preparing to add our infrared detector to the system. When completed, CHARMS will be a one-of-a-kind, world-class facility that will give Goddard the unique capability to make ultrahigh-

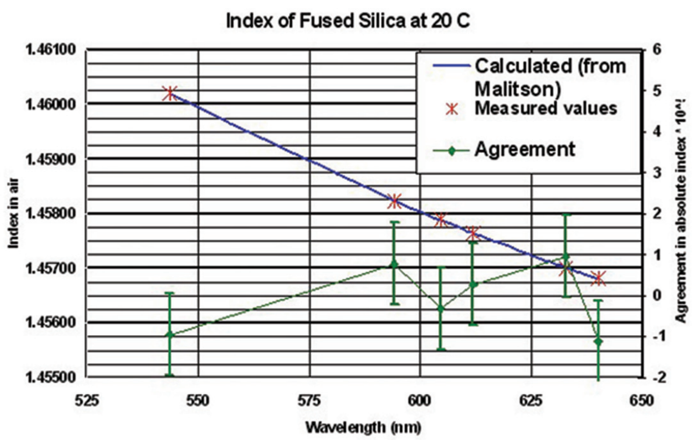


Figure 4: Calculated and measured spectral index of refraction of used silica for selected wavelengths at 20˚ C.

accuracy index of refraction measurements. In FY 2004 we will be supporting (and will be supported by) the James Webb Space Telescope (JWST) / Near Infrared Camera (NIRCam) project. The NIRCam instrument is currently an all-refractive design, and will be the first of many NASA missions and instruments to benefit tremendously from the work we have done.

Summary:

Many future NASA instruments are being designed to operate at cryogenic temperatures, yet measurements of the refractive index of constituent optical materials for these instruments have not been made to sufficient accuracy. By implementing several innovative features to improve upon previous refractometry efforts, CHARMS will allow us to measure the refractive index of these materials to unprecedented (10^{-5}) accuracy. These innovative features include ultrahigh-accuracy, absolute, cryogenic metrology and an instrument design that allows us to perform our measurements at the operational temperature of the optical material (rather than measuring it at room temperature and extrapolating how we think it will behave at some other, vastly different temperature). Goddard will benefit immediately from CHARMS through unprecedented knowledge of refractive index for future optical instrument designs. In addition, Goddard will possess the only facility in the world (that we know of) capable of making these measurements for the international scientific community.

The criteria for successful completion of CHARMS are: (1) to measure the refractive index in the infrared of materials in the current JWST/NIRCam optical design to fifth-decimal accuracy, and (2) to establish a capability at Goddard to provide broadband cryogenic through room temperature refractive index data for future NASA missions. Technical risk factors that might prevent us from achieving success lie in (1) the difficulty of developing the absolute cryogenic metrology to sufficient accuracy and (2) the development of thermal design that provides sufficient sample temperature knowledge and control.

Oriented Nanocomposite Extrusion

Principal Investigator: Dan Powell (code 542.1)

Other Investigators: Carl Stahle (553), Hugh Bruck (UMCP), Sateesh Bajikar (contractor)

Initiation Year: FY 2003

FY 2003 Authorized Funding: $56,500

Actual or Expected Expenditure of FY 2003 Funding: In-house machining, $11,000; retroactive ion etching, $7,500; RandCastle Extrusion Equipment Inc., $11,000; Umicore Equipment Processing, $2,000; JFC Technologies, $3,500; University of Kentucky, Center for Applied Energy Research, $3,000; Miscellaneous & Lab Equipment, $2,000; Dr. Hugh Bruck, University of Maryland at College Park, $22,500

Status at End of FY 2003: To be continued into FY 2004 with additional DDF, $35,000

Expected Completion Date: October 11th, 2004

Purpose of the Investigation:

We are developing a technology to orient the direction of carbon nanotubes (CNTs) within a variety of substances, something that has not yet been accomplished in a readily scalable context. Carbon nanotubes are strong yet flexible carbon tubes with diameters as small as one nanometer. This technology could usher in the development of solar sails, morphable aero-elastic surfaces and structures, and ultra-low-weight heat shields, to name but a few. The improvements of oriented CNT composites over current (randomly aligned) material capabilities are dramatic. CNTs have an axial modulus (referring to strengths in the longitudinal direction of the fibers) greater than one Tera-Pascal, allowing their composites to be potentially stronger than steel in tension yet flexible with near-infinite life. CNTs axially conduct heat at greater than 3,000 watts per milli-Kelvin and conduct electricity six orders of magnitude better than copper, allowing their composites to de-localize any concentrated heat source and behave as ballistic electrical conductors. Such properties are enhanced when the nanotubes are aligned in their substrate and aimed in one direction like lane dividers on a highway instead of at random angles.

Recent progress on the characterization and preparation of CNTs has enabled the development of oriented CNT composites for a variety of NASA missions, such as the Webb Space Telescope gossamer sunshield. Not only could a CNT film rapidly redistribute the heat load to a relatively even distribution across the structure, but it could (1) filter electromagnetic, particle, and gamma radiation, (2) have increased strength to resist puncture, and (3) arrest propagation of any tear as it develops. Our work addresses the challenge of extruding oriented CNTs in laminate (layered) fashion and characterizing the material of the resulting composite. We use a device shaped somewhat like a harmonica to channel and orient the nanotubes. We aim to leverage recent advances presented in the literature on the oriented laminate extrusion of carbon nanotubes through such a microchannel mold in low-viscosity substrates. This will enable us to meet the challenge of producing thermally stabilized and preferentially mechanically stiffened thin-films capable of selective electromagnetic interference (EMI) shielding.

Accomplishments to Date:

The stated research objectives and development plan for the first year of this work were to: develop a new class of multifunctional composites for use in NASA programs; quantify best practice manufacturing techniques and material characteristics for oriented CNT composites comprised of various substrates; identify capability requirements for tailoring composite properties for mission-specific application; and identify technology requirements for manufacturing scale-up and industry transfer. Our research development plan was to: design, and fabricate standard-interface microchannel extrusion head capable of depositing a 40- to 100nm-thick, oriented CNT monolayer using low-viscosity substrates documented in literature; build a 1" x 1" directional multi-layer composite by incrementing the CNT monolayer extrusion direction; quantify the composite's structural composition, thermal conductivity, directional mechanical stiffness, and RF Compatibility; optimize and document the best-practice multi-layer extrusion process for each substrate; and iterate though substrates of interest, in order of increasing viscosity, leveraging the knowledge gained.

Most of these objectives were not met in FY 2003, and progress in pursuing the development plan was limited in large part by a number of one-time events and conditions. As has been widely reported by other investigators, delay in the receipt of DDF funds pushed back the start of FY 2003 DDF investigations by nearly five months. Additional delays were imparted by the nearly simultaneous receipt of funds and financial freeze, which delayed acquisition of key supplies and extrusion equipment by another significant period. Delays in the execution of purchase requests also impacted critical path acquisitions and continue to be an issue in light of the accounting backlog. Graduate student support was also tragically setback by the death of the UMCP doctoral student supporting this work halfway through the investigation.

In spite of these unusual and crippling delays, significant progress has been made; and seamless integration of what we call phase-one accomplishments into phase-two objectives should still be attainable in a timely fashion. Phase one is the oriented extrusion of CNTs and CNT ropes in viscous substrates (polyimide, polyanaline, carbon pitch, polyester film, etc). And phase two is the covalent cross-linking of CNTs with substrates. (Phase three is manufacturing scale-up for industry adoption.)

The initial investigation was broken into four distinct but complimentary tasks: rheometric measurements of MCNT-loaded polymers at temperatures near their processing temperature; computational fluid dynamics (CFD) to size the initial microchannel cross-section; guide design of the microchannel extrusion die; and the design and fabrication of the extrusion die and die-housing. Rheometric measurement of 3-5 MWNT-loaded polymer samples was conducted resulting in identification of a variety of polymer substrates, which may be appropriately employed in this investigation. Microchannel cross-sections and aspect ratios were also significantly altered from those initially proposed based upon rheometric investigation of MWNT-loaded polymers within the 0-3wt% range. Identification of both a novel shear-thickening phenomena and accelerating exponential viscosity curve resulted from rheometry study of polymers loaded with MWNTs in the 1-3wt% range.

Extensive Navier-Stokes CFD was conducted to solidify parity of actual MWNT-loaded polymer viscosity while qualifying conceptual die designs. Knudsen number analyses were conducted for each candidate polymer to verify the appropriateness of the no-slip assumption in the Navier-Stokes development. A three-dimensional Lattice-Boltzmann one-phase MATLab code was developed and successfully qualified for channel cross-sections and melt viscosities of indicated by the Navier-Stokes CFD discussed above as a precursor to a two-phase code developed to study in situ alignment of MWNTs flowing though channels of varying dimensions. This investigation's substrate viscosity tolerance, MWNT-loading range, and extrusion die metrics were successfully bounded through closed-form Navier-Stokes analysis, and verified through Navier-Stokes and Lattice-Boltzmann FEA simulation.

Design for fabrication of a flexible and scalable microchannel extrusion has been completed and accepted by Code 553.0 for fabrication. Design of the microchannel die housing and twin-screw extruder (TSE) interface is nearly completed but was delayed by priority flight-failure investigation work, which was not anticipated. Fabrication of the microchannel extrusion die was delayed until November 1, 2003 due to personnel shortages and lack of facility availability within Code 553.0. Although significant progress was made, as previously mentioned, design of the die housing was also delayed due to a priority flight-failure investigation within Code 543.0. Patent disclosures were filed related to this work and full patent applications are expected to be submitted in the third quarter of FY 2004. In addition, four journal articles are under draft related to several novel aspects of this work. Other journal submissions are expected to be forthcoming through FY 2004. Additionally, the initial findings stemming from this work were presented at the NASA Tech Briefs Conference in Boston in October 2003.

Planned Future Work:

Pursuant to completion of phase 1 of this investigation and in preparation to undertake phase 2, the FY 2004 development objectives and research plan are as follows: We will continue development of a new class of multifunctional composites for use in NASA programs; continue to document best practice manufacturing techniques and material characteristics for oriented CNT composites comprised of various substrates; identify capability requirements for tailoring composite properties for mission-specific application; and identify technology requirements for manufacturing scale-up and industry transfer. Our research development plan, delineated in the previous section, has been slightly modified. One change is that we will fabricate a standard-interface microchannel extrusion head capable of depositing a 700- to 1000-nm-thick oriented CNT monolayer using low-viscosity substrates documented in literature.

Summary:

The concept of microchannel extrusion of nanotubes itself is novel, as is using the boundary-layer flow properties realized at these scales to preferentially orient nanostructures in situ. If realized, this flexible, high-strength, thermally and electrically conductive, thin-film nanocomposite -- produced via a readily scalable and unprecedented twin-screw extrusion process -- will make practical the development of solar-sails, morphable aeroelastic surfaces and structures, ultra low-mass heat shields, and flexible low-mass multi-agent radiation shields, among other developments of interest. This will likely replace a significant portion of the $14 billion graphite epoxy industry overnight. Moreover this is a platform technology upon which others can build, and the application potential really cannot be estimated. The five-year goal of this investigation remains the transfer to industry of a scalable process appropriate to replace graphite epoxy as a base product in aerospace and preferentially enhance polymer products globally. The three major challenges to the development of oriented CNT composites are (1) the oriented extrusion of CNTs and CNT ropes in viscous substrates, (2) covalent cross-linking of CNTs with substrates, and (3) manufacturing scale-up for industry adoption in the near future.

Large Angle Flexure

Principal Investigator: Claef Hakun (code 544)

Other Investigators: Ken Blumenstock (544), Jeff Bolognese (543)

Initiation Year: FY 2003

FY 2003 Authorized Funding: $20,000

Actual or Expected Expenditure of FY 2003 Funding: Support hardware, misc. vendors $2,000; and Swales (draftsman and fabrication) $18,000

Status at End of FY 2003: To be continued into FY 2004 with remaining PRs funded from FY 2003

Expected Completion Date: April 2004

Purpose of the Investigation:

The goal of this investigation is to develop a large-angle flexure, or joint, that can be used to support the movement of telescope parts at cryogenic temperatures, a few degrees above absolute zero. The large-angle flexure (LAF) provides precision rotary motion traditionally accomplished with the use of ball bearings. Many cryogenic mechanism applications require a high duty cycle -- that is, millions of cycles per mission lifetime. It is difficult to guarantee robust operation using ball bearings due to the lack of suitable lubricants at cryogenic temperature. The use of flexures eliminates the need for lubrication and allows for infinite life (high duty cycle applications) at cryogenic temperatures. The LAF represents an innovative approach to achieving large-angle flexure-based rotary motion that will have high-transverse and moment stiffness (allowing for precision motion) and low-torsional stiffness (or twisting strength, which reduces heat loss, crucial in a cryogenic environment).

Accomplishments to Date:

Our DDF FY03 effort succeeded in designing the large-angle flexure geometry. Various configurations were investigated using finite element software.A design was selected that optimized radial stiffness versus torsional stiffness. In addition, we designed a rotary actuator, which will be used to drive and characterize the flexure. The final design of the prototype unit is currently being detailed. The resulting drawings will then be fabricated.

Planned Future Work:

The prototype unit (Figure 1) will be fabricated, assembled and characterized. The torsional, radial and axial stiffnesses will be quantified and compared to analytical results. The resulting database will allow a streamlined design process for development of flight-unit LAF bearings as required on future missions.

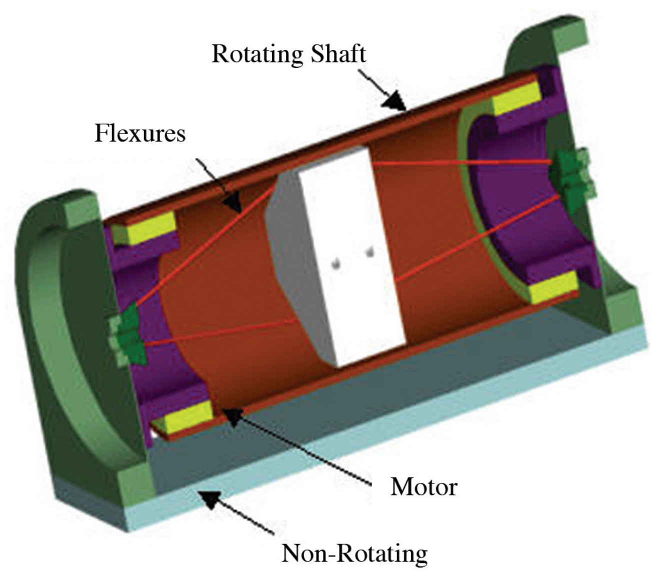


Figure 1. Large-angle flexure cross-section

Summary:

The successful completion of this project will result in an innovative rotary-motion device capable of moving optical components to precise positions, less than 5 arcseconds, over a large angular range at cryogenic temperatures, a few degrees above absolute zero. Many of NASA's future projects require highly reliable precision positioning of optical components at cryogenic temperature, and Goddard will benefit from having this technology in-house. This device will afford engineers a design option to accomplish such motions. The success of this device is based on requirements that will be developed for future cryogenic mechanisms. In general, the device must be capable of precision motion and have low power dissipation at cryogenic temperature. Technical risks may arise when the system is pushed to the limit in terms of motion, precision, power and stress induced in the flexures. However, the key properties of the materials we are using are well understood; and as long as we stay within well-defined limits, we expect no technical risks that would preclude the use of this device for future missions.

Magnetic Optical Wheel Solenoid (MOWS)

Principal Investigator: James Marsh (code 544)

Other Investigators: Ken Blumenstock (544), Claef Hakun (544), Kate Hale (544)

Initiation Year: FY 2003

FY 2003 Authorized Funding: $59,000

Actual or Expected Expenditure of FY 2003 Funding: Support hardware, misc. vendors $10,000; Code 547 fabrication, $22,000; and Sigma Space $27,000

Status at End of FY 2003: To be continued into FY 2004 with remaining PRs funded from FY 2003

Expected Completion Date: February 2004

Purpose of the Investigation:

The goal of this investigation is to develop a method to position various optical elements used in modern telescopes, such as gratings, with precision accuracy. Currently an optical wheel is used, and this rotates the optical element (colored filter or grating) into place for any given observation. The method has worked well in the past, but modern telescopes -- particularly those with multiple grating used for spectroscopy -- require positioning at a precision level greater than what traditional optical wheels can provide, that is, finer than 5 arcseconds. We are developing a mechanism that uses a magnetic solenoid in conjunction with the optical wheel that will provide the needed precision. We call this the Magnetic Optical Wheel Solenoid, or MOWS. The technology will eliminate the need for precision optical wheels requiring tight tolerances for their motors, gears, sensors, and bearings. We use an energized magnet with a ball-and-groove kinematic, or curved, mount to position optical elements to the 5-arcsecond level of precision.

Accomplishments to Date:

For the DDF FY03 effort we designed, assembled and performed initial tests on the repeatability of the kinematic mount and solenoid system. Each time the solenoid was activated and the mating occurred, we took a measurement of the position using flat mirrors and a theodolite, a surveying instrument used for measuring horizontal and vertical angles. The results obtained were encouraging but did not meet the ±5 arcsecond requirement generated at the beginning of the effort. Rather the results ranged from 1.1 to 38.7 arcseconds off the initial mated position in the horizontal direction and from -8.2 to 58.2 arcseconds in the vertical direction. Figures 1 and 2 below show these relative errors for multiple matings.

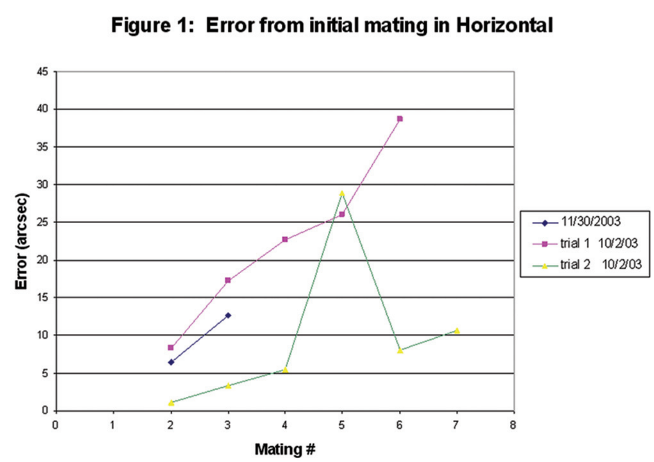


Figure 1: Error from intial mating in Horizontal

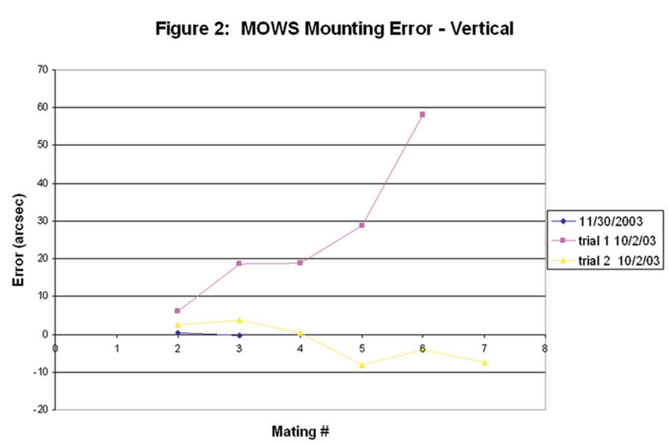


Figure 2: MOWS mounting error - Vertical

Figure 1 depicts how, during the majority of the testing, the error was observed to increase at each mating. Close inspection of the mating surfaces showed that the grooves had indentations and scratching from the multiple matings. This inspection led us to conclude that the titanium semi-balls were contacting the aluminum grooves with enough force to dent the surface and cause increasing error in the position.

We therefore decided upon a new approach to the kinematic mount. Instead of using actual grooves, we will insert pairs of steel pins. This will provide hard surfaces that the titanium semi-balls could contact without causing damage. Thus the kinematic mount may reach the required ±5 arcsecond repeatability. A contractor from Sigma Space is currently assisting us in the next-generation design of MOWS.

Planned Future Work:

We plan to receive the second-generation design and hardware from Sigma Space in 2004. Assembly and testing of the hardware will complete the MOWS development effort. With the uncertainty of FY 2004 DDF funds and no present alternative source of funding, planned cryogenic testing will have to be delayed until funding becomes available.

Summary:

The MOWS technology provides an innovative method for placing multiple optical elements in a single light path. The potential payoff to Goddard is the development and use of this new technology, which could provide instruments with increased precision while reducing costs and risks. The criteria for success is proving the technology will function as predicted in a simulated laboratory environment, and, if it doesn't, being able to understand the deficiencies and what it will take to overcome these deficiencies. The major factor that has prevented achieving success was our inability to procure or attain the necessary hardware to breadboard our concept within the procurement system changes given to us during FY 2003.

Hyperspectral Sensor for Image-Based Wavefront Sensing

Principal Investigator: Bruce Dean (code 551)

Other Investigators: Lee Feinberg (443)

Initiation Year: FY 2003

FY 2003 Authorized Funding: $26,000

Actual or Expected Expenditure of FY 2003 Funding: Matlab Image Acquisition software, optical components, diversity camera deployment and mount, CCD camera $13,000; DSP Optimized Software Libraries $6,500; Matlab Real-Time Workshop SharcLab software $7,500:

Status at End of FY 2003: The 2003 DDF objectives have been completed. Additional AETD internal funding has been obtained as follow-on work to this proposal.

Expected Completion Date: completed

Purpose of the Investigation:

The purpose of this investigation is to study a technique for measuring "piston error" in a segmented mirror telescope by using images produced by the telescope. Large mirrors that are composed of many smaller mirrors typically have small misalignment errors due to differences in position as measured with respect to gaps between the mirror segments. These piston errors can severely degrade image quality and must be corrected by moving the mirror segments into their nominal positions. Measurement of these piston errors can be accomplished using a form of image-based wavefront sensing (not unlike the technology behind the current generation of LASIK eye surgery), but specifically utilizing hyperspectral imaging. This refers to the analysis of certain wavelengths of light most sensitive to piston error. By looking for these target wavelengths, we can efficiently correct for piston error using a reduced wavelength set instead of analyzing the entire range of wavelengths collected by a telescope, as is the case with large, deployable, space-based telescope facilities.

Accomplishments to Date:

Work has shown that the hyperspectral approach is a viable alternative to the DFS (dispersed fringe sensor). The analysis indicates that hyperspectral imaging technology can be used to recover piston and other misalignment errors in a segmented aperture telescope. This work is also the first application using hyperspectral imaging for image-based wavefront sensing. The principle is based on the concept of "wavelength-diversity" and the fact that intensity variations due to piston error vary strongly as a function of wavelength. In summary, hyperspectral imagery has been utilized to search for target wavelengths. These target wavelengths are then baselined for data collection. Once these optimal wavelengths are known, accurate piston detection can be realized with this reduced wavelength set.

The modeled OPD (optical path difference) is shown in figure 1 along with the mirror segment geometry in the rightmost figure. This aperture is identical to the aperture selected for the James Webb Space Telescope (JWST). As illustrated in this figure, the assumed errors are piston errors due to errors in the mirror segment positions along the optical axis. The OPD shown in figure 1 (next page) is used to calculate the diversity defocus data as a function of wavelength. This data is representative of a hyperspectral diversity data set collected by a hyperspectral camera at a defocused image plane. The data is shown in figure 2 (next page).

Inspection of figure 2 clearly indicates a variation in intensity as a function of wavelength. Therefore, the piston errors from the telescope OPD also vary in wavelength as imaged by a CCD array. In an earlier investigation, we found that image-based wavefront sensing accuracy is more accurate in cases where the spectral contrast of the aberration signal is strongest. By analyzing the OTF (optical transfer function) of the data shown in figure 2, the spectral contrast of the piston aberration signal does vary from wavelength to wavelength. Furthermore, there are certain wavelengths that yield stronger contrast in piston than do others. For example, the intensity data for the wavelengths, λ 0.81463 and λ 0.82683

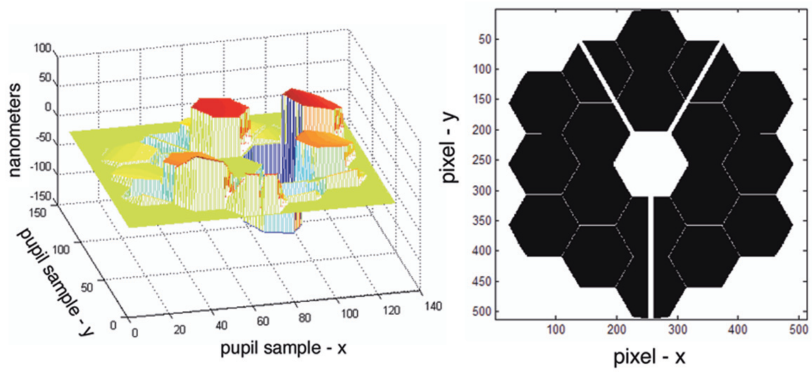


Figure 1. Optical Path Difference Data for an 18 Segment Hexagonal Aperture. Segment Layout for Telescope Aperture

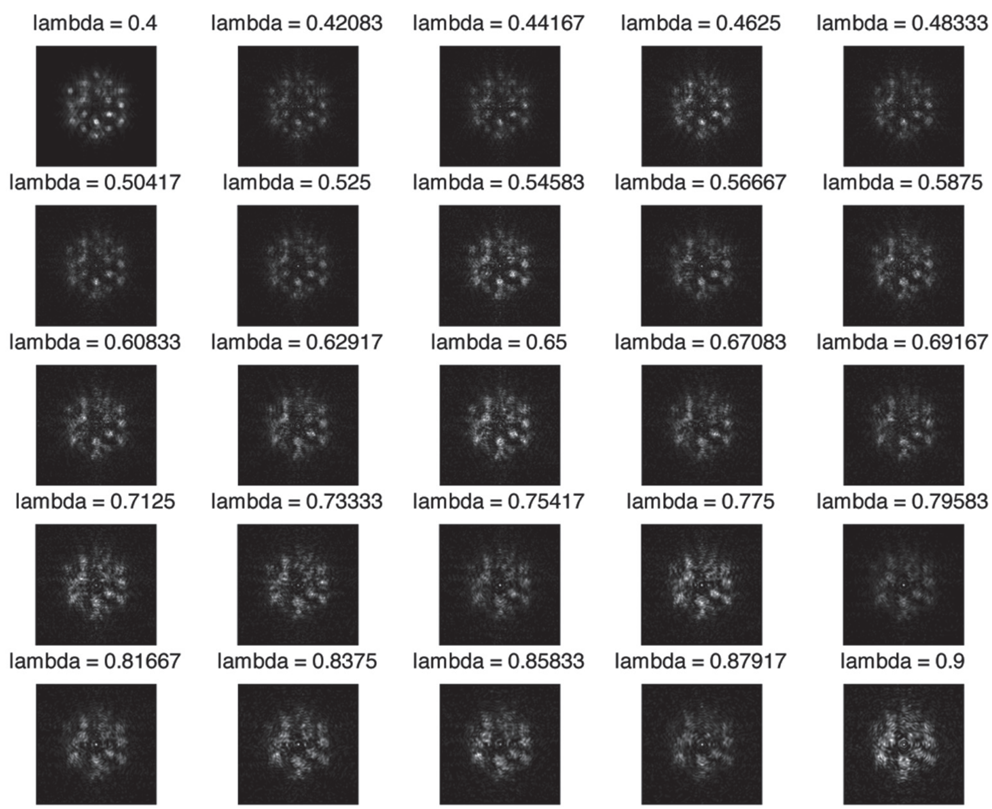


Figure 2. Hyperspectral Diversity Data Set. Wavelength Units are Microns.

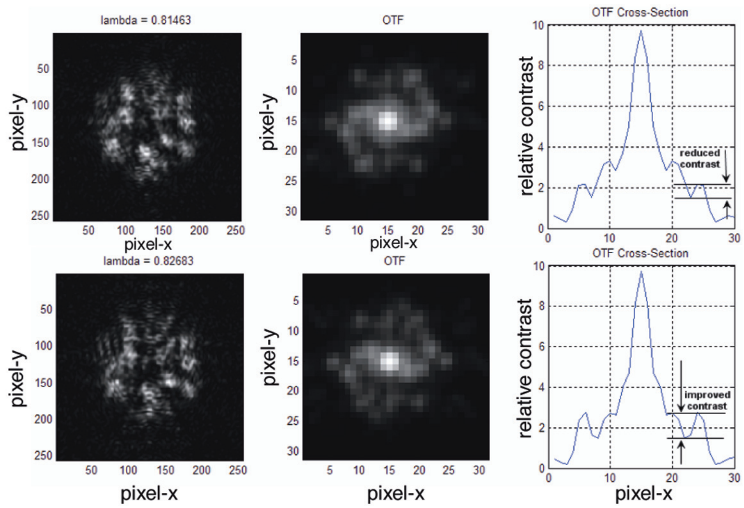


Figure 3. Intensity and OTF Data at Distinct Wavelengths.

are shown in Figure 3. By examining the OTF cross-section, it is clear that some contrast improvement is obtained at the slightly larger wavelength. As a result it is expected that wavefront performance will also be improved based on the analysis presented in our earlier investigation.

Planned Future Work:

Having demonstrated the utility of hyperspectral imaging to identify wavelengths for improved piston contrast, a subset of data (that is, multi-spectral) can now be selected from a hyperspectral data set, based on the criterion of improved OTF contrast. This data represents a set of target data wavelengths for use by an image-based phase-retrieval algorithm to the recover OPD errors. In future work, phase-retrieval

analysis will be performed on these multi-spectral data sets to compare phase-retrieval recoveries to cases where the "maximum-contrast" criterion was not applied. The data will be collected in the Building 5 IDL labs where the hyperspectral camera is currently undergoing calibration and test.

Summary:

This project has demonstrated the use of hyperspectral imagery for piston detection in a segmented aperture array, which can correct for image distortion in large telescope mirrors caused by the regions where the smaller telescopes comprising the array are fitted together. Hyperspectral imagery – concentrating on target wavelengths most affected by the piston error (regions of segmentation) – offers a simpler image-correction alternative to the "mainstream" DFS method. An example of the type of breakthrough that this technology may enable for Goddard is a method to completely align a segmented aperture system, such as that intended for JWST, with a single optical element, as opposed to the multi-phase "coarse + fine" approach currently envisioned for JWST and other future segmented telescopes. This research will also enable us to evaluate the wavelength parameter space yielding the most effective wavefront sensing results. The criterion for success was the successful demonstration of improved contrast at discrete image wavelengths comprising the hyperspectral data set. The main technical factor limiting success would have been the improper modeling or understanding of the diffraction effects at multi-wavelengths of the hyperspectral data set.

New research will leverage off of the work in this DDF award, and additional funding has been used to procure hyperspectral imaging hardware. This hardware has been received and is currently undergoing laboratory calibration. Additional testing will be performed utilizing the hyperspectral camera to match theoretical results discussed in this report with data obtained with the hyperspectral camera.

Tomographic Processing for Image-Based Wavefront Sensing

Principal Investigator: Bruce Dean (code 551)

Initiation Year: FY 2003

FY 2003 Authorized Funding: $4,500

Actual or Expected Expenditure of FY 2003 Funding: Funding for two students through Code 564 -- $3,000; Deconvolution Software -- $1,500

Status at End of FY 2003: The 2003 DDF objectives have been completed. Additional AETD internal funding, leveraging off of DDF research, has been obtained as follow-on work to this proposal.

Expected Completion Date: completed

Purpose of the Investigation:

The purpose of this investigation was to develop a more efficient means to measure aberrations, or distortions, in telescope mirrors through a process called wavefront sensing using a "tomographic" computational method. Current measurement techniques require the entire image; our computational-based sampling technique has the potential to greatly speed up processing time, which is crucial for space-based missions. The goal was to develop an algorithm and test this on simulated data. Our computational approach segments images into smaller arrays of pixel values. Phase-retrieval (an aberration measurement technique) is then performed on each sub-array and then recombined to find a phase-map that is simultaneously consistent with the phase-retrieval estimates over each sub-array of pixel values. This algorithm is particularly useful for pre-flight sub-aperture testing of large optical systems, that is, for cases where only a small fraction of the optical system can be illuminated.

Accomplishments to Date:

A new phase-retrieval algorithm has been developed based on a tomographic reconstruction technique. The dynamic range, effectiveness, and accuracy of the approach have been tested on a sparse data set. Additional funding, leveraging off of this DDF research, has been obtained to further develop and implement this algorithm on DSP computing hardware. The algorithm flow-chart is shown in Figure 1. This algorithm approach is based on the concept of adaptive-diversity, a known aberration used to modulate the optical response, but modified to handle sparse data for this study. An example of a data set used as input to the algorithm in is shown in figure 2. Such a data set would result from a telescope aperture that is sparse in the light collecting area of the primary mirror and imaging a point source or star. Optical coherence is assumed since a point source object is self-coherent by definition. For the study of algorithm performance considered here, a known "coma" aberration is used to generate the intensity data. Such an aberration is typical for a misalignment error in a two-mirror telescope system. Results from the phase-retrieval algorithm can then be compared to the known starting phase value to test wavefront sensing accuracy.

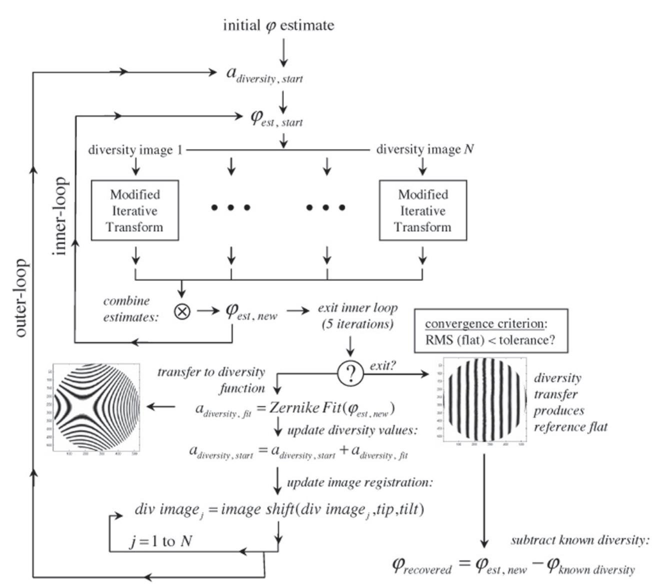


Figure 1. Adaptive Diversity Algorithm used for Tomographic Processing

An initial estimate of the phase is used to start the algorithm that is designed to simultaneously process multiple intensity images differing by varying diversity defocus levels. Preferably, these defocus levels are chosen according to the prediction presented in "Diversity Selection for Phase-Diverse-Phase-Retrieval" [Dean et al., J. Opt. Soc. Am. 20 (8) 1490-1504, (2003)]. The individual images are processed using a modified Misell-Gerchberg-Saxton iterative transform method. The iterative transform method was developed in the early 1970s as a means of reconstructing phase from intensity data by iteratively transforming back and forth between conjugate Fourier domains. The implementation of this algorithm is "data-based" rather than model-based in the sense that algorithm parameters, such a defocus level, F/#, wavelength, and pixel size, are estimated directly from the image data itself as a pre-processing step prior to implementing phase-retrieval. In practice, the values of these parameters affect how the Fourier transforms are implemented in the iterative-transform algorithm. By contrast, a model-based approach typically requires a detailed optical-ray-trace model to generate diversity information such as defocus, while the data-based method requires only the image data itself.

After processing by the modified iterative-transform procedure, the individual estimates obtained from each image are combined using a weighted average (denoted by the ⊗ symbol) to form the phase estimate $\varphi_{est\ new}$ as illustrated in Figure 1 and labeled as the "inner-loop." It is well known that the iterative-transform approach stagnates quickly after a relatively small number of iterations. Therefore, at least from a computational standpoint, the overall algorithm efficiency is improved by restricting the inner-loop iterations to a small number. In the implementation considered here, this process is repeated for a total of five iterations as shown in Figure 1 to take advantage of the initial rapid gain in convergence that is characteristic of the iterative-transform method, while avoiding stagnation.

After exiting from the inner-loop, a phase-map is produced that is partially consistent with each image used in the data set. This phase map is then decomposed into a Zernike basis set:

$$\vec{a}_{\text{diversity fit}} = \text{Zernike Fit} \left(\varphi_{est\ new} \right) \quad \text{[equation 1].}$$

Note that $\vec{a} = (a_1, a_2, ..., a_{15})$, since there's $1/2\ (z_{order} + 1)(z_{order} + 2) = 15$ terms in the order four basis set. These numerical values are then transferred to the previous diversity function using the update

$$\vec{a}_{\text{diversity, start}} = \vec{a}_{\text{diversity, start}} + \vec{a}_{\text{diversity, fit}} \quad \text{[equation 2].}$$

Higher-order Zernike basis sets can be used for these decompositions, but the order four set is adopted as a result of a trade between computational performance (i.e., higher-order fitting takes longer) and capturing a reasonable number of optically significant terms. In this basis set, global (referring to the "global" $\varphi_{est,\ new}$ phase-map) tip and tilt correspond to the coefficients, a_2 and a_3, which are used to re-adjust the locations of individual diversity image centers by the same amount for each diversity image. An updated diversity data set is then produced for re-processing by the inner-loop via return by the outer-loop. In this way, image registration is adaptive and is based on the amount of global tip-tilt returned in the outer-loop iterations. Image registration errors that may be present due to the image centering pre-processing step are thus averaged out as the global tip and tilt are minimized by the algorithm process. Similarly, imperfect knowledge in either the image F/#s or diversity defocus values for individual images can lead to the recovery of an overall global defocus error. Previous diversity defocus values are thus adaptively updated according to the recovery of global defocus in the phase estimate, $\varphi_{est,\ new}$. In turn, as the amount of diversity defocus varies in each image, aberration recovery varies with differing amounts of defocus and thus feedback is incorporated into the recovery process. This process is continued until the global defocus error is driven to zero during the recovery process.

A couple of observations can be made that clarify the algorithm operation. First, the aberration amplitude may far exceed one wave after exiting the inner-loop portion of the algorithm. As is well known, the classical iterative transform method cannot, by itself, recover multi-wave aberrations. The algorithm will thus produce a wrapped phase map, $\varphi_{est,\ new}$. However, a special aberration fitting procedure can be applied to the wrapped phase data to return at least some portion of the multi-wave aberrations to the variable, $\vec{a}_{\text{diversity, fit}}$. These numerical values are then transferred to the diversity function and treated as known phase values. In this way, a multi-wave aberration can be recovered incrementally by successively applying an aberration fitting procedure to intermediate wrapped phase maps. As more and more of the aberration is transferred to the diversity function following successive iterations around the outer loop, the estimated phase, $\varphi_{est,\ new}$ no longer wraps since the multi-wave (unknown) aberration values become incorporated as part of the diversity function. As a result, $\varphi_{est,\ new}$ begins to resemble a reference flat as more and more of the aberration content is transferred to the diversity function. To emphasize this point, the process of aberration transfer is illustrated in figure 1 by including calculated interferograms from both the adaptive diversity function, $\vec{a}_{\text{diversity, fit}}$ and also the reference flat, $\varphi_{\text{est, new}}$, as the algorithm nears convergence for an arbitrarily selected wavefront dominated by astigmatism.

The algorithm has been applied to process a sparsely supported data set as shown in Figure 2. The known phase is shown in the left figure, while the resulting defocused intensity data is shown on the right. The right figure shows the data used as input to the phase-retrieval algorithm.

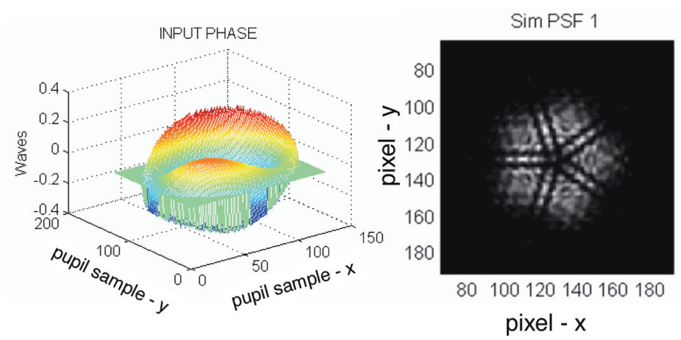


Figure 2. Known Phase-Aberration and Input Intensity Data.

The sparse aperture consistent with this data is shown in Figure 3 below.

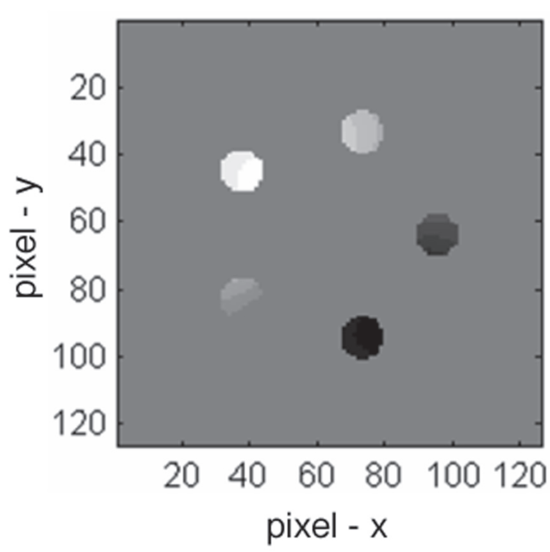


Figure 3. Sparse Aperture used in the Model.

The phase-retrieval results are shown in Figure 4 giving a comparison of the known input values (blue-dot) with the recovered values (red-circle). The RMS difference (error) is only 2 nm RMS, indicating that highly accurate phase-recoveries are possible using this algorithm approach with sparse or incomplete data.

Planned Future Work:

The algorithm will be implemented on DSP (digital signal processor) computing hardware to further enhance performance. The goal is to make "image-based wavefront sensing" return phase values in near real-time to the data collection by the CCD array. Further simulation works will also be done to understand the algorithm accuracy as a function of the pupil coverage.

Summary:

This project has demonstrated that highly accurate phase-retrieval is possible using incomplete data on a sparse-aperture array through the use of simple, low-cost, and computationally efficient image-based wavefront sensor. This technology is intended for deployment on space-based telescopes, which would be of benefit to Goddard. The criterion for success has been the successful demonstration of algorithm performance on a sparsely illuminated pupil, or opening, in a telescope optic piece. The main technical factor limiting success would have been the presence of insufficient information in the intensity data to allow recovery of the optical phase. The algorithm performance shows that sufficient information was present to allow accurate aberration recovery.

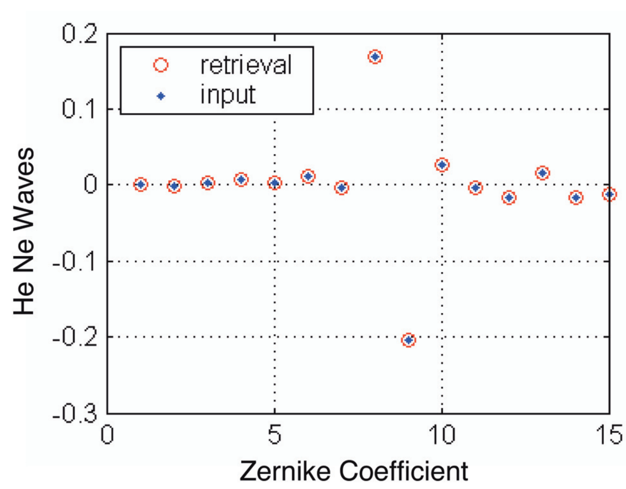


Figure 4. Comparison of Input and Recovered Phase-Coefficients.

An Interferometer for Low Uncertainty Vector Metrology

Principal Investigator: Ronald Toland (code 551)

Other Investigators: Doug Leviton (551), Lou Worrel (ManTech), Seth Koterba (NASA Academy)

Initiation Year: FY03

FY 2003 Authorized Funding: $40,000

Actual or Expected Expenditure of FY 2003 Funding: ManTech Systems Engineering Corp, $22,100; Swales Aerospace, $4,100; BMI Supplies, $3,600; Melles Griot, $2,400; Newport, $1,800; Coastal Optics, $1,800; McMaster-Carr, $500; Electrim Corp., $800; EJ Enterprises, $800; Amazon.com, $700

Status at End of FY 2003: To be continued in FY 2004 with funds remaining from FY 2003 and possible JWST or FKSI project funds

Expected Completion Date: February 2004

Purpose of the Investigation:

We are building an instrument for vector metrology (a method to measure the alignment of a satellite's many components) that will be more accurate, less costly and require fewer operators than instruments currently in use. Such technology is crucial for telescopes to provide increasingly sharper resolution, particularly for space-based interferometers, a new frontier. Improved vector metrology plays a vital role in the assembly of future space instrumentation and spacecraft. For scientific instruments and spacecraft, the relation of a detector to a mirror, the placement of an optical bench inside an enclosure, and accounting for the deflection of a weighted structure under gravity all require precision metrology. Currently, instruments such as theodolites set the standards for mechanical tolerances and thus the science goals possible. These instruments leave a small level of uncertainty in measurement, however, of approximately 2 arcseconds. Considering the hierarchal nature of a satellite (components within instruments within a spacecraft), errors begin to stack up. We can lower this uncertainty somewhat through multiple measurements and statistical analysis, but the costs in time and manpower associated with such procedures becomes prohibitive past a certain level. For projects that require measurements to the sub-arcsecond level -- such as the proposed Fourier-Kelvin Stellar Interferometer -- theodolites cannot perform to the level required. *Our goal is to develop a means to measure spacecraft component orientations using interferometric techniques (involving lasers) to reduce uncertainties to 0.1 arcseconds or better.*

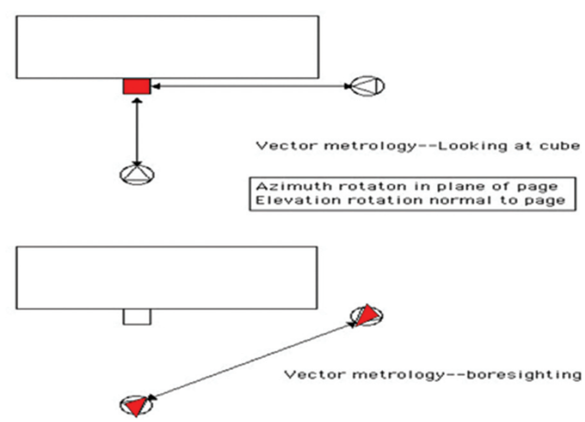


Figure 1: Vector Metrology Example

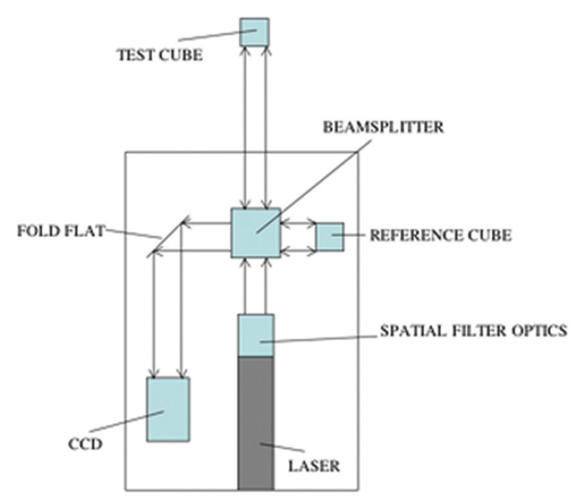


Figure 2: Simplified Optical Layout of Twyman-Green Interferometer

Accomplishments to Date:

In our project, a Twyman-Green interferometer (shown in figure 2) replaces the telescope on the theodolite. Essentially, a collimated laser beam passing through a beamsplitter is divided in two, one beam segment (the reference leg) reflecting off an alignment cube serving as a reference surface, the other (the test leg) striking the mirror or cube under test before returning to the beamsplitter, where both beams are re-combined and passed to a CCD camera by a fold flat. The CCD images the fringe pattern (interferogram) formed by the combined beams; the number and orientation of the fringes seen are directly related to the angle between the reference surface and test surface. Thus, if we can calculate the amount of tilt present in the interferogram, we know the orientation of the test cube face surface normal. By placing this interferometer on a stage rotating in azimuth and elevation, with position readout via high-accuracy optical encoders and measuring vector tilts through automated fringe analysis, we eliminate many of the sources of error in a theodolite (operator error, limited sensitivity of imaging through a telescope, etc.) while providing the same information—gravity-referenced measurements of alignment cube orientations.

Early on, we submitted a new technology report to the tech-transfer office on the design of the interferometer system (which we have taken to calling a “theoferometer” as a mix of its theodolite use and interferometer operation). Our last communication with the tech transfer office indicated it was being evaluated by the patent office for possible patent application.

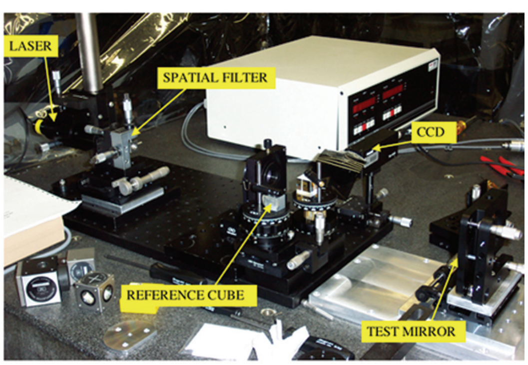


Figure 3: Breadboard Twyman-Green Interferometer

During the funding lockdown, we borrowed enough parts from other labs to build a breadboard Twyman-Green interferometer in the lab space we had been given. (figure 3). We used this interferometer to test out alignment techniques, investigate design requirements and ensure the vibration levels of the lab were adequate to our purpose. In addition, sample fringe patterns from this interferometer were used to test the robustness of the fringe analysis software we had to write.

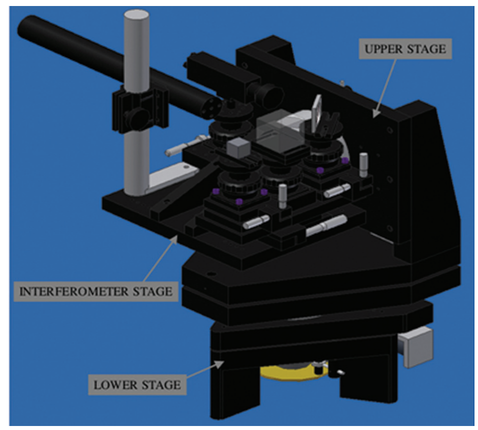


Figure 4: 3-D Mechanical Model of Theoferometer Design

With the software ready and parts available, we began assembling the theoferometer. We found our design to be sound, with a few unanticipated problems. While fairly stable, there is some drift in the upper and lower stages, as seen by the absolute rotary encoders used. Our design to mount the readheads for the encoders needs improvement; the simple post and screw system we designed is too coarse for the fine adjustments needed to properly position the readheads with respect to the encoder disk (see figure 5). These encoders, recently developed at Goddard by Doug Leviton, function by imaging a pattern of fiducials and code bits imprinted on a silicon disk mounted to the each air bearing. The code bits indicate the (sequential) number of the fiducial found below them. The fiducials are evenly spaced in a ring about the center of the disk. By knowing the pitch, or spacing, of the fiducials, we can assign an angular value to each fiducial: for example, if fiducial 1 is at 0 degrees, and if each fiducial is 0.5 degrees apart, then fiducial 15 would mark 7.5 degrees. In each image, at least three fiducials are visible, allowing us to calculate the angular position at the center of the image -- the position reported by the encoder software. The images are taken by a CCD mounted at one of a readhead (an aspheric lens is bonded into the other end); an LED on the opposite side of the disk provides the needed illumination -- the flash for the camera. This system is naturally very sensitive to the position of the camera and lens: too close, and the code bits move off screen, too far away, and the bits are too close together to be distinguished. Focus, too, is critical to getting a good image, and thus a good encoder reading. Our readhead mount design did not allow for the separate adjustment of these parameters (loosening the mount to adjust focus also changed the position of the readhead with respect to the disk), which led to many long hours spent adjusting the readhead position until good images could be obtained.

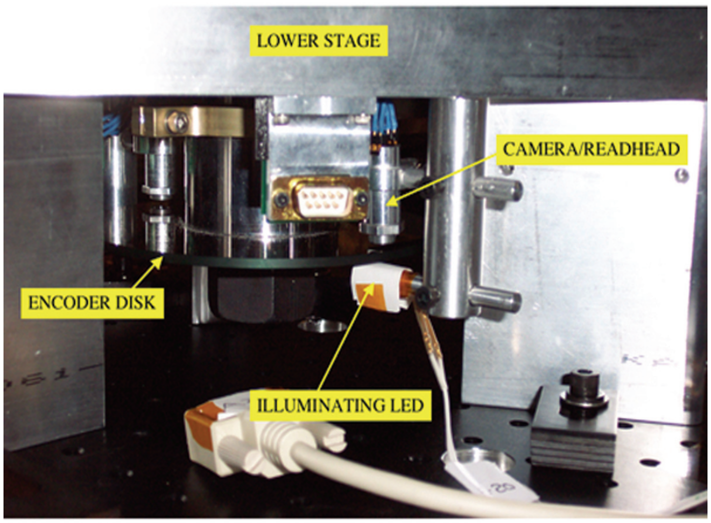


Figure 5: Close up of Encoder Readhead Mount

The greatest oversight was in the location of the center of gravity of the upper stage of the instrument. When we attached the upper stage to the lower air bearing, we found we needed to add weights to the interferometer base plate and to the interface plate between the lower and upper stages to properly balance them. Without the extra weights, the interferometer, when rotated, would reach a point where the motor moving it could no longer stop its motion. It would "tip over." Similarly, we found the level of the lower stage disturbed by the upper if the center of gravity of the upper stage was not located above the axis of rotation of the lower stage.

Thankfully, with the weight balanced on the upper stage, the motors used to rotate the air bearings perform quite well. The interface software also runs smoothly and is able to adequately control the theoferometer from a local PC. The interferometer itself yields good, high-contrast fringes, and vibration does not seem to be a problem with getting good data—our (perhaps overly) rugged design does its job. Currently, the theoferometer is fully constructed and undergoing testing to characterize its accuracy and usefulness as a metrology instrument (see figure 6). We anticipate results within the next few months.

Planned Future Work

Testing of the theoferometer will continue through early FY2004. As stated above, we plan to have full results by February 2004. With testing of the prototype completed, design of a new and improved system will begin. The current model uses air bearings for rotation, which are very accurate but require an air supply to function and thus limit the theoferometer's portability. We plan to replace these air bearings with highly accurate mechanical bearings and use dual readheads on the rotary encoders to correct for error in bearing rotation. We also plan to change the laser from the current HeNe frequency-stabilized model to a diode laser with adequate coherence length. This will greatly reduce the weight and size of the interferometer and allow us to substantially shrink the size of the entire unit, again contributing to its portability and usefulness. An additional anticipated improvement is the full automation of the movement of the theoferometer, allowing automated alignment and data taking, further increasing its ease of use over a theodolite. With these improvements, we see the theoferometer maturing from a test unit to an instrument capable of replacing the theodolite as our main vector metrology instrument.

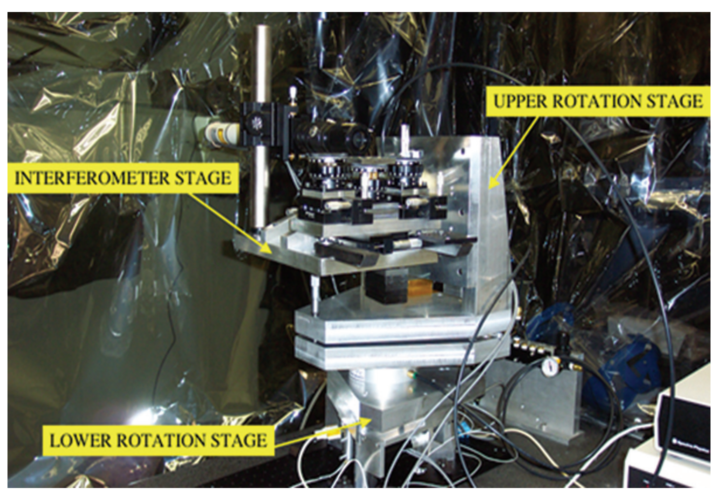


Figure 6: Fully Assembled Theoferometer

Summary:

The project has several innovative features: the fringe analysis technique used to measure the tilt of a metrology cube surface; the Goddard-developed encoders used to read angular position; the use of CCD technology to eliminate human error; and the automation of alignment data-taking, which saves time and increases ease-of-use. For Goddard, successful construction of this instrument will aid in the building of more ambitious spacecraft in the future, such as stellar interferometers. Our technique may also replace legacy metrology instruments with more accurate, less costly units that will require fewer operators and less time to use. The criteria for success is to demonstrate the ability to take gravity-referenced vector data with Type A (NIST standard) uncertainty of 0.2 arcseconds or better. There are several technical risk factors that might prevent achieving success, although we continue to minimize these risks. These include: (1) vibration, which could prevent us from obtaining good fringe patterns; (2) fringe analysis, particularly if the software cannot achieve the needed accuracy using the Fourier analysis technique; (3) alignment, where the non-orthogonality of axes of rotation could lead to errors in vector data; (4) knowledge of gravity, referring to problems with using a reflective pool as a gravity reference -- for example, an inability to get a fringe pattern off the surface of the pool would lower the accuracy of the gravity reference and lead to reduced usefulness of theoferometer as metrology tool; and (5) stiffness, in which a sagging structure could induce errors in vector measurements if drifts from movement of the structure are indistinguishable from drifts in the motors or encoders.

Cooling Large Telescopes and Instruments to 4 K Using Adiabatic Demagnetization Refrigerators (ADR)

Principal Investigator: Michael DiPirro (code 552)

Co-Investigators: Edgar Canavan, Michael Jackson, James Tuttle, Peter Shirron (552) and Todd King (541)

Initiation Year: FY 2003

FY 2003 Authorized Funding: $70,000

Actual or Expected Expenditure of FY 2003 Funding: In-house: $70,000

Status of Investigation at End of FY 2003: To be continued in FY 2004 with Additional (FY 2004) DDF Funding of $70,000

Expected Completion Date: December 2004

Purpose of Investigation:

We have designed and are building a next-generation cooling system to chill telescope instruments planned for satellites to 4 Kelvin (K), or four degrees above absolute zero. This is the cooling requirement for future, large infrared space telescopes such as SAFIR, the Single Aperture Far InfraRed Observatory. Such a cooling device needs to last for many years and effectively cool telescope detectors with pixel areas far greater than what is flown today. Our design is an adiabatic demagnetization refrigerator (ADR), which uses a superconducting magnet instead of mechanical parts. One of the most basic cooling systems, an "ice-box" technology, uses helium dewars to chill an instrument like ice cools a bottle; but carrying enough helium to last several years in space is impractical. Mechanic coolers, or cryocoolers, use pumps to compress (and recycle) gas not unlike a kitchen refrigerator but are not efficient below 10 K. An ADR can operate in this temperature range with an efficiency of 75% or better of Carnot, a point of maximum thermodynamic efficiency. The current generation of ADRs for space, such as that planned for the Astro-E2 mission, are effective at cooling a 36-pixel detector to micro-Kelvin temperatures but still require a bulky dewar to attain a low starting temperature. Our ADR is designed to cool detectors with thousands of pixels (more pixels equals more heat and greater cooling challenge) and to operate at a higher starting temperature -- which eliminates the lowest-temperature mechanical cryocooler stage (a system of coolers inside coolers), reduces weight by 90%, simplifies the system, and increases its reliability.

Accomplishments to Date:

During the past year we have accomplished several of our original goals. First, a quick background of the instrument: We are building an ADR to cool relatively large power loads (10-100 milli-Watts) at 4 K and rejecting that heat to an external cryocooler operating at 10 K. The ADR magnet consists of eight short coils wired in series and arranged in a toroid to provide self-shielding of its magnetic field (figure 1). This will save the mass that would have been used for passive or active shields in an ordinary solenoid. This amounts to about 30% of the mass (or about 1.5 kg) in our small version, and higher percentages in higher cooling power, larger versions. (See figure 2.) The toroid has a 130 mm outer diameter and will produce an approximately 3 Tesla (T) average field. In the initial demonstration model, the toroid coils are wound with ordinary NbTi superconducting wire and operated at 4 K. A second version will then use Nb_3Sn wire to provide complete 10 K operation. As a refrigerant for this temperature range we will use either $GdLiF_4$ or GdF_3 crystals, pending tests of their cooling capacity per field and thermal conductance. Preliminary indications are that these materials are superior to the previously used material, gadolinium gallium garnet (GGG). We will use gas gap heat switches to alternately connect the refrigerant in the toroid to the cold load and the warm heat sink. A small continuous stage will maintain the cold end at 4 K while the main toroid is recycled.

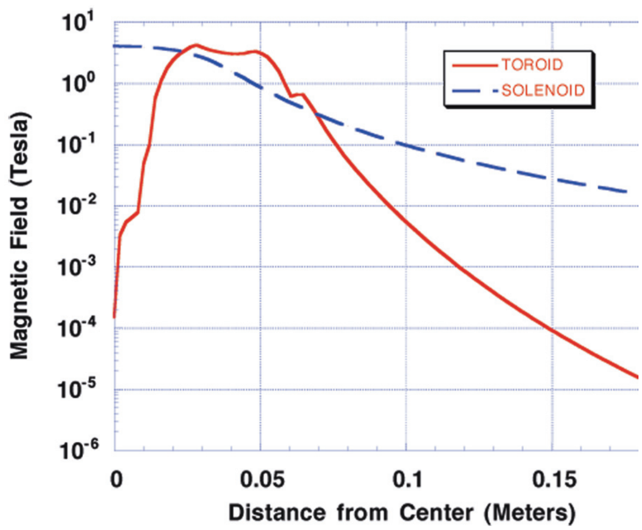


Figure 1. Calculations of the magnetic field in an optimized solenoid (dashed blue line) and an 8 segment toroid (solid red line).

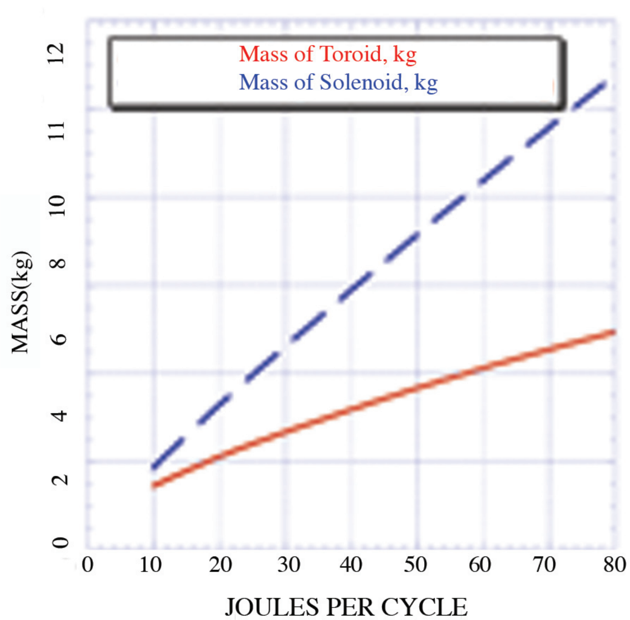


Figure 2. Calculations of the optimized mass of a solenoid (dashed red line) and toroid (solid red line) 10 K to 4 K system.

We have completed design of an initial toroidal ADR for operation between 10 and 4K (figure 3). We have fabricated the first coil form and found a structural issue with the initial mandrel design. It was subsequently redesigned with minimal impact to the overall toroid, and rewound with 14,500 turns of NbTi superconductor successfully (figure 4). This coil is about to be tested at 4.2 K. We have started fabrication of the other seven mandrels necessary to complete the toroid. We are buying the remainder of the superconducting NbTi wire to wind these mandrels. Due to the late arrival of funds, we got a late start on our procurements but have received a fluxgate magnetometer system that will allow us to measure stray fields from our toroid down to the level of 20 nanoTesla (0.2 milligauss).

We have experimented with a passive gas gap heat switch (an example of which is shown in figure 5) for use at 10 K, and have found that a charcoal getter gives us exactly the turn off temperature required. We have tested GdF_3 and $GdLiF_4$ materials for magnetization and heat capacity vs. field and temperature. See figure 6.

We have begun working with a vendor to produce crystals of these materials that have a high enough thermal conductivity for our high cooling power goal. Meanwhile, we are procuring GGG crystals for use in place of GdF_3 and $GdLiF_4$. A paper entitled "Continuous Cooling from 10 K to 4 K Using a Toroidal ADR" has been accepted for publication in Cryogenics.

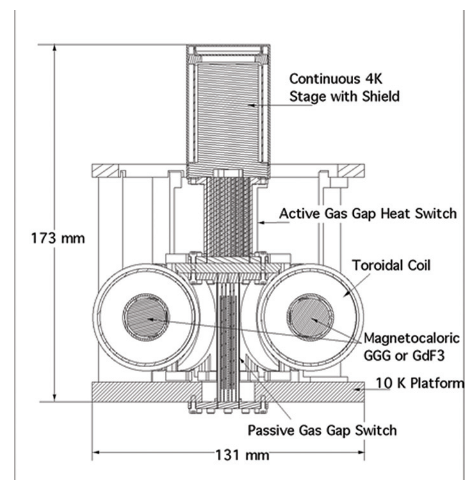


Figure 3. Line drawing of assembled toroidal ADR.

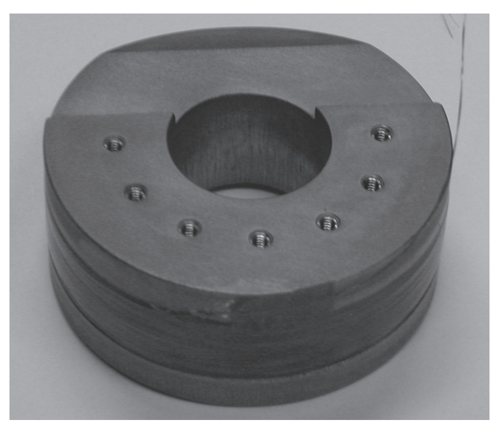


Figure 4. 50 mm outer diameter toroid segment with NbTi wire wound on a magnesium mandrel.

Planned Future Work:

During the second year we will assemble the complete system of magnets, GGG, suspension system and heat switch and test this in an existing dewar that is already configured to simulate a 10 K interface. We will then measure the thermal performance of the toroidal ADR. In particular we will measure the efficiency at various cold end temperatures and heat inputs (power absorbed at 4 K divided by the power rejected at 10 K), and the cool down rate from 10 K. We will also measure the fringing field in this system configuration.

We have closely watched the development of small-diameter, high-performance Nb3Sn wire under a Small Business Innovative Research (SBIR) contract. The contractor has achieved success beyond his initial goal, fabricating usable long lengths of this react-then-wind wire. This wire is suitable for our use up to 11 K in the final version, and we hope to be able to procure lengths long enough for our toroid if we receive second year funding. If this is the case, then we will make a second toroid of similar design using this wire and do a true 10 K to 4 K demonstration.

Figure 5. The interior of a passively operated gas gap heat switch

Summary:

We have shown through calculation and some material characterization tests that it is feasible to provide cooling using an ADR, with no moving parts, to cycle between 4 and 10 K. We are presently building such an ADR to provide between 10 and 100 milli-Watts of cooling. The cooling requirements for many future space-based science missions cannot be met by the current generation of cooling devices without the added bulk of dewars. Goddard will benefit from new ADR technology because it is envisioned that a space-qualified version of this system will provide the low-temperature stage on a cryocooled large space telescope like SAFIR.The criteria for success is the creation of an adiabatic demagnetization laboratory system that is easy to operate, can provide 10 to 100 milliwatts of cooling at 4K and reject the heat to 10K, and has a thermodynamic efficiency of at least 50% (and hopefully as much as 75%) of Carnot. Technical risk factors that might prevent achieving success are (1) obtaining fine superconducting wire that can operate with high enough magnetic field at 10K to provide the required cooling at the required efficiency, and (2) obtaining good-enough internal thermal conductance in the magnets and cooling stage to cycle the ADR frequently enough to obtain the higher cooling powers.

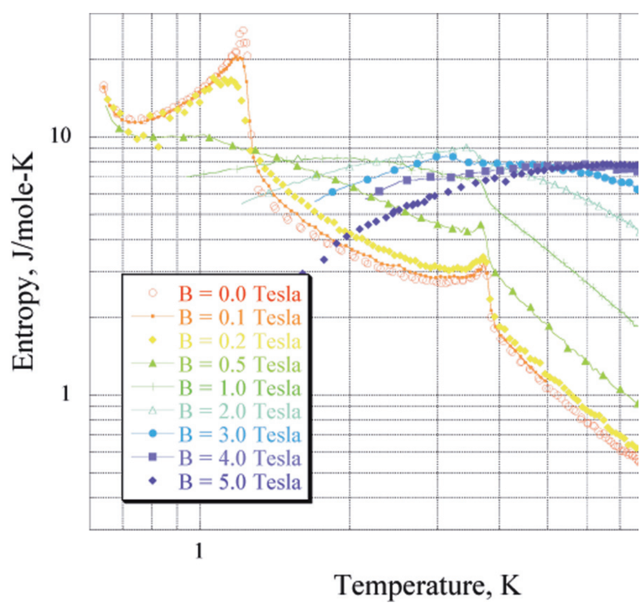


Figure 6. Heat capacity data of a sample of GdF_3 from which the magnetic entropy and cooling power are derived. The low temperature peak is the magnetic ordering of GdF_3 as expected. The second peak at 3.8 K indicates an impurity of Gd_2O_3 which must be removed to improve performance.

Epitaxial Silicon for Cryogenic Bolometers

Principal Investigator: Christine Allen (Code 553), Robert Silverberg (685)

Co-Investigators: Richard McClanahan, Timothy Miller, Harold Isenberg, John Abrahams and Robert Mitchell (553)

Initiation Year: FY 2003

FY 2003 Authorized Funding: $50,000

Actual or Expected Expenditure of FY 2003 Funding: SOI wafers, Soitec, $20,000; testing (ceramic boards, connectors, and cryogens), $17,500; Lawrence Semiconductor, $12,500 (pending)

Status of Investigation at End of FY 2003: To be continued in FY 2004, with additional DDF funding, requested at $32,500

Expected Completion Date: August 2004

Purpose of Investigation:

This investigation is to establish a new method of producing doped-silicon detectors for infrared astronomy and X-ray astrophysics. Doping is the process of adding an impurity to a silicon wafer to make it a better conductor. Silicon detectors on upcoming space missions need to operate at temperatures below 4 Kelvin, or 4 degrees above absolute zero, and require precisely doped resistors. Due to the variability of the doping process, approximately 80-90% of doped silicon wafers do not meet the requirements for such missions and are rejected. We are investigating the efficacy of replacing the most important yet troublesome step of the fabrication process -- doping with an ion implanter, which has proven to be extremely difficult to control and reproduce -- with "predoped" material procured from qualified vendors. The doping method here is called epitaxial growth, a process whereby single-crystal silicon is deposited in a precisely controlled fashion onto a seed crystal. Dopants are introduced during this deposition process and are uniform throughout the deposited layer. Multiple wafers can be produced with identical doping. If one wafer is characterized, the other wafers in the batch have known resistance. We aim to determine whether epitaxially grown silicon can be produced of a quality comparable to that produced by ion-implantation. This would provide us with a reliable and less expensive method for obtaining starting material of guaranteed quality for detector fabrication. Success in this project would greatly improve semiconductor detector production yields and performance and reduce fabrication manpower while impacting production schedules in a positive manner.

Accomplishments to Date:

The High Resolution Airborne Wide-band Camera (HAWC), the premier Facilities Instrument for the Stratospheric Observatory for Infrared Astronomy (SOFIA), and Astro-E2 X-Ray Spectrometer use detectors with some form of silicon-based resistive element as the sensor. The technology used for HAWC requires a series of nine ion implantations into each silicon wafer to create a precisely tailored net dose. Due to the variability of the ion implantation process, generally only one or two wafers from a starting batch of 10 to 12 fall within the target range, and the rest are rejected. The resistance of the doped silicon is extremely sensitive to temperature variation $R(T)=R_0 * e^{\sqrt{(To/T)}}$, where R_0 and T_0 are dependent on the concentration of impurities. This dependence makes the doped silicon a very good sensor, but also makes it very difficult to reproduce, as the impurity concentration must fall within a small percent of the target range to be usable.

During FY 2003 we laid the foundation for processing and evaluating detectors with epitaxial silicon and comparing them with ion-implanted silicon. We procured 50 silicon-on-insulator (SOI) wafers for epitaxial growth. We implanted three SOI wafers with a distribution of implant doses. These wafers were cut into quarters to provide four samples per dose. One quarter from each implanted wafer has been processed into resistors. We are measuring the temperature dependence of the resistance of these doses. This is performed in a Kelvinox-25 dilution refrigeration system in the temperature range of about 50-400 milli-Kelvin. Figure 1 shows the temperature dependence of the resistance for three sam-

ID	Phos.Dose (e^{18}/cm^2)	Boron Dose (e^{18}/cm^2)	Calc. Net Density (e^{18}/cm^3)	R0	T0	$\boxed{\text{R(100 mK)}}$
21F	6.907	3.641	2.376	172	17	88 Mohm
21B	7.084	3.734	2.416	256	16	74 Mohm
21C	7.325	3.861	2.537	424	9.7	8 Mohm

Table 1. Summary of doping levels and coefficients to exponential curve fit for three ion implanted samples.

ples. There is a marked difference in the resistance as a function of ion dose. Table 1 gives an overview of the doping levels for each of these samples, the calculated coefficients of the exponential fit to the data, as well as the calculated resistance at a representative operating temperature. A second quarter of each ion-implanted wafer has been reserved to act as a calibration standard for epitaxial growth. The vendor will measure the actual doping level in these samples and reproduce that doping density using epitaxial growth.We are presently awaiting award of this contract so that we may proceed with this portion of the investigation.

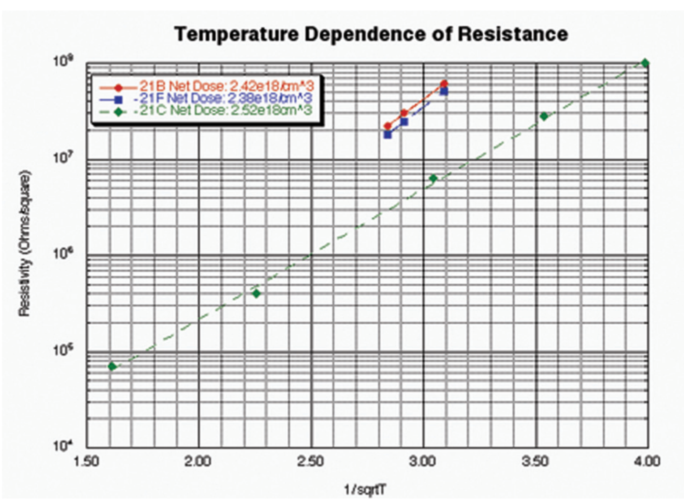


Figure 1. Temperature dependence of three different resistors, ion-implanted with doses varying by a small percent in net ion density.

Planned Future Work:

The continuation of this investigation in FY 2004 involves obtaining epitaxial silicon and repeating the process of evaluating the temperature dependence by fabricating and testing chip resistors. With the advent of the new procurement system at Goddard, we have been unable to obtain a contract award for this work. Once we obtain this material, we will then use the epitaxial silicon to produce detectors with the “pop-up detector design” used for the Caltech Submillimeter Observatory facility and SOFIA/HAWC. Detectors produced will be tested for frequency-dependent electrical noise, and comparisons will be made to the noise obtained from HAWC arrays. A second basis of comparison will be the Astro-E2’s XRS calorimeter test results. The XRS deep-diffusion doping ion implant levels formed the basis for the calculations of doping density for this investigation. In that doping scheme, single doses of phosphorous and boron are diffused uniformly throughout the detector layer of silicon.

This doping, uniform in density with respect to depth into the silicon, most closely mimics that which we are attempting to achieve with epitaxial silicon growth and has proven to have the lowest level of intrinsic noise of any ion-implanted detector.

Summary:

Semiconducting detectors can be fabricated with a new method of well-controlled impurity doping, which is reproducible and provides a guaranteed supply of starting material for detector fabrication. For Goddard, we will enable the production of semiconducting bolometers and calorimeters with guaranteed doping characteristics. The yield of usable devices will increase from an average of about 10-20% to nearly 100%. This increased yield will reduce the necessary manpower to fabricate flight wafers and will positively impact production schedules. The criteria for success is the demonstration of (1) a working, semiconducting detector with frequency-dependent noise less than or equal to that which can be produced by ion implantation, and (2) the reproducibility of the new process that the silicon-coating (epitaxial-growth) provider can use to reproducibly hit the targeted doping levels. Technical risk factors cannot be established at this time as the project is under continued investigation. Administrative risks are to the scheduling, as we have been unable to obtain timely awards for non-emergency contracts for services and supplies during FY 2003. We cannot begin detector production and testing until the contract for epitaxial silicon is awarded, and this is causing a delay in the major portion of the investigation. Technical risk factors will be reported in FY 2004.

Cryogenic Polarization Chopper for Millimeter and Sub-Millimeter Waves

Principal Investigator: James Chervenak (code 553) and Dominic Benford (685)

Co-Investigators: Julie Abato (685), Julia Sakamoto (NASA Academy)

Initiation Year: FY 2003

FY 2003 Authorized Funding: $50,000

Actual or Expected Expenditure of FY 2003 Funding: Custom machining, $5,000; Fabrication costs, $22,000; FTS lab operations, $20,000; Lab supplies, $3,000

Status of Investigation at End of FY 2003: To be continued in FY 2004 with funds remaining from FY 2003

Expected Completion Date: March 2004

Purpose of Investigation:

The Detector Systems and Infrared Astrophysics Branches plan to make strategic advances in ultrasensitive measurement of the polarization of millimeter waves. Polarization refers to the degree to which light's magnetic and electric fields are vibrating in one direction, which provides clues to the physics of the light source. The ultimate goal of this work is to compete for a space-based telescope to study the polarization of the cosmic microwave background (CMB), the afterglow of the big bang. Microwave radiation ranges from 1 to 3 millimeters in wavelength. A proposed NASA mission called CMBPOL or the Inflation Probe could, in the next decade, complete the work of COBE and WMAP in probing the fluctuations in the early universe at a small fraction of a second after the big bang. It would do so by analyzing the degree of polarization imprinted on the cosmic microwave background by gravitational radiation produced at the end of the inflationary period. The search for signatures of gravitational interactions in the CMB is a high science priority. In the interim, numerous opportunities for technology demonstrations and groundbreaking astrophysics on ground-based and airborne observing platforms will arise. We have used this DDF to create an optical component for a receiver for polarized millimeter waves and have built a test bed for the evaluation of polarization-sensitive components at millimeter waves.

Accomplishments to Date:

The focus of this work is to design, fabricate and study optical components suitable for modulation of millimeter-wave polarization. We chose a grid of linear arrays of superconducting tunnel junctions that can be placed in a millimeter wave beam, selected for polarization, and then modulated from transmissive to reflective for that polarization. Such a technology is critical for building a polarization sensitive receiver. In addition, the component operates at ultralow temperatures so that it can be interfaced with our ultrasensitive bolometry without adding photon background and noise to the detector system. The modulation is actuated by an applied current, which in principle does not elevate the temperature of the component, and obviates the need for moving parts in the optical system, which is difficult to achieve at these cryogenic temperatures. Our goal with this project is to demonstrate a polarization modulator with multiple polarization orientations with suitable electrical performance (actuation from 0 ohm, a reflective state, to greater than 1,000 ohms, a transmissive state), optical performance (50 percent modulation of an unpolarized beam in a Fourier Transform Spectrometer, or FTS), and thermal performance (operation below 1 K) of the component built in Code 553 using our test bed in Code 685.

As shown in figure 1, we chose a design with weak links (which carry away built-up charge *after* readout) in a superconducting wire for the modulation element. We planned to build up parallel modulating wires on a silicon wafer using an amorphous silicon layer as weak link and a silicon dioxide layer for insulation between orthogonal wires that modulation the complementary polarization. We found that ultrathin films of NbTi met our desired criterion for electrical modulation, allowing the wire to vary from 0 ohm to greater than one kilo-ohm in resistance.

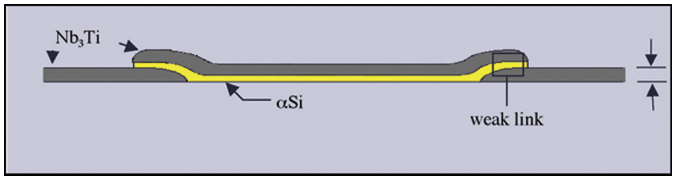


Figure 1. Side view of the weak-link sub-unit. A linear array of 150 such units makes up each wire of the polarizer grid. The length of each sub-unit (<10 microns) is optimized for the wavelengths of interest (1-3 mm)

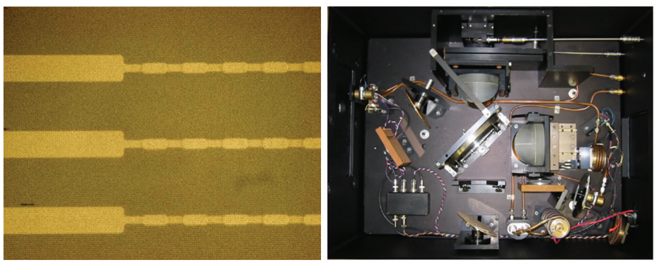


Figure 2. A photomicrograph of a fabricated polarization modulation component. The dark regions are the Si substrate and the light regions are a close-up view of the series arrays of weak links made of NbTi and amorphous Si.

We were able to demonstrate wires of superconducting material with the requisite weak links using optical lithography. In the photomicrograph shown in figure 2 (a 100x100 micron area of a 25,400-square-micron chip), features are less than 3 microns wide with less than 5-square-micron junction area. Arrays of millions of weak links have been fabricated with appropriate dimensions for actuating reflection and transmission of submillimeter and millimeter waves. Electrical tests have been performed for superconductivity and normal state resistance of the wires, which indicate successful implementation of the design.

We have successfully operated the FTS in the laboratory in Code 685. The beam is created and collimated with non-polarizing optics and then routed through our samples and to a cryogenically cooled sensor to readout the beam power. The cryostat containing the sensor was modified to accept polarimeters, and is capable of cooling them down to a temperature of about 1 Kelvin. The FTS chamber has been built to permit transmission, absorption, reflection measurement of dual polarizations as a function of wavelength. Everything was designed, purchased, and assembled. The FTS will be back online in 2004 to complete testing of the polarization modulator.

Planned Future Work:

Key issues to be addressed are the precise measurement of the weak link critical current. Successful design will require a uniform actuation current from wire to wire in an array to enable actuation of the entire grid. The thermal testing (which can be verified by monitoring the low resistance non-actuated wire while other wires are actuated) will also be performed. The main thrust of the work will be the obtainment and analysis of spectra from these devices.

Summary:

This project's innovative feature is to create a novel type of optics that can enable polarization modulation techniques compatible with ultrasensitive bolometers, which are instruments that measure slight changes in heat, or energy. The development of polarization-sensitive millimeter wave receivers will give Goddard a competitive edge in future missions to measure polarization of the cosmic microwave background, which require great sensitivity. The criterion for success is the demonstration of a polarization modulator meeting rigid electrical, optical and thermal requirements. The invention of a technique to modulate polarization via a purely electrical technique appears feasible given the capabilities of our fabrication facility. One program need, however, is time -- that is, time to complete the desired infrastructure buildup and testing to be certain that the program can be successful.

RF MEMS for Microwave Instruments

Principal Investigator: Eric Simon (code 555)

Co-Investigators: Mary Li (553), Fernando Pellerano (555), Eric Chikando (Morgan State University), Chiagozie Nwabuebo (George Washington University)

Initiation Year: FY 2002

Funding Authorized in FY 2002: $60,000

FY 2003 Authorized Funding: $40,000

Actual or Expected Expenditure of FY 2003 Funding: In-house, $40,000

Status of Investigation at End of FY 2003: Completed in FY 2003

Purpose of Investigation:

This investigation aimed to provide groundwork for developing large, foldable antennae that, once deployed on satellites, would provide high-resolution for earth- and space-science investigations. An example is the STAR antenna, short for Synthetic Thinned Aperture Radiometry. This is a simple T- or Y-shaped antenna that can easily fold inside a launching vehicle yet, once unfurled, still provide the same resolution as a more "solid" antenna. Such technology is crucial because antennae with 30-meter diameters are needed for future missions in order to, for example, measure soil moisture globally from space. Traditional antennae with such diameters would be difficult to launch. However, the "synthetic thinned" types of antennae (which rely on electronically-induced synthetic apertures) require high-quality Radio Frequency (RF) switches. These are toggling devices that distribute energy through different channels. The requirements for remote-sensing microwave radiometers and radars are already beginning to surpass what can be achieved with conventional switch technology. One new technology is radio-frequency micro-electromechanical systems (RF MEMS), which could meet or surpass these future requirements for microwave instrumentation. Our effort focused on bringing RF MEMS expertise to Goddard and explored fabrication and characterization of an RF MEMS switch.

Accomplishments to Date:

During FY 2003 we were able to fabricate several wafers with prototype switches in the Detector Design Lab (DDL) at Goddard. These switches were based on a capacitive shunt configuration. Figure 1 shows a schematic of the switch with the different layers. Each wafer consists of a significant number of chips, each of which has about 12 switches (see figure 2). Significant challenges were encountered during the fabrication process. These problems had to do primarily with the process controls needed to accomplish the desired circuit patterns. One of the problems was etching the gold transmission lines. These lines are 4 μm thick and the etching process was too aggressive, which resulted in over-etching or narrower lines than desired, therefore, changing the characteristic impedance of the device. The second problem was the sacrificial layer used to layout the suspended membrane. We tried several processes and neither resulted in a satisfactory membrane. In most cases the membrane collapsed resulting in a short of the switch. Figure 3 shows a scanning electron microscope (SEM) image of one of the devices.

Although the devices produced were not able to actuate, we were able to test the through-lines in order to characterize the basic RF performance of the devices. For this purpose a test station was developed that enabled on-wafer probing and RF characterization up to 110 GigaHertz (GHz). This was achieved through a combination of DDF and other

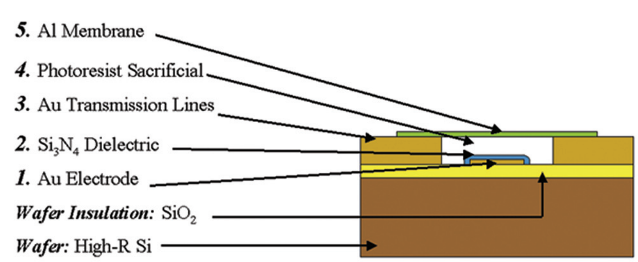


Figure 1: RF MEMS Switch Schematic

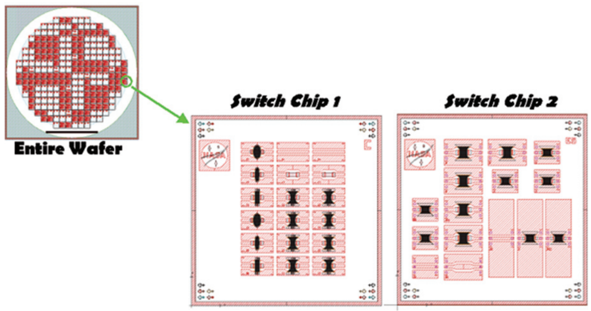


Figure 2: Wafer and Chips with RF MEMS Switches

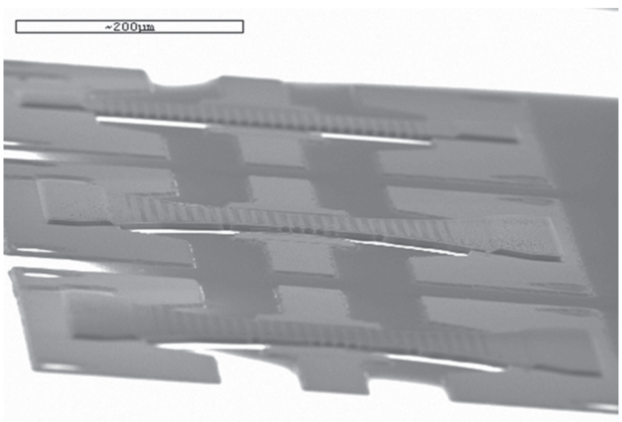


Figure 3: SEM Image of an RF MEMS Switch

institutional resources. Figure 4 shows a picture of the test station. It combines two major pieces of equipment, one is the probe system itself, and the second a vector network analyzer (VNA). We characterized the impedance and insertion loss of a co-planar waveguide (CPW) thru-line as shown in figure 5. These results were not expected to be perfect because the over-etching problem changed the dimensions of the line. This, however, could be compensated for in the models and checked for agreement with the measurements. Once these adjustments were made we obtained good agreement between the measured data and the models as demonstrated in figure 6.

While the processes used for fabrication of these devices still needs work, the results to date are very encouraging. We have gained confidence in our modeling and testing capabilities and learned significantly about the specific fabrication issues that affect these devices. We believe the primary objectives of bringing RF MEMS expertise to Goddard and exploring the fabrication and characterization of an RF MEMS switch have been accomplished. Findings from this DDF were published as part of the paper titled "Effects of Environmental and Operational Stresses on RF MEMS Switch Technologies for Space Applications" authored by Muzar Jah (Code 562), Eric Simon and Ashok Sharma (562). This paper was presented at the International Microelectronics And Packaging Society (IMAPS) Topical Technology Workshop on MEMS, Related Microsystems and Nanopackaging in November 2003.

Figure 4: On-wafer Test Station

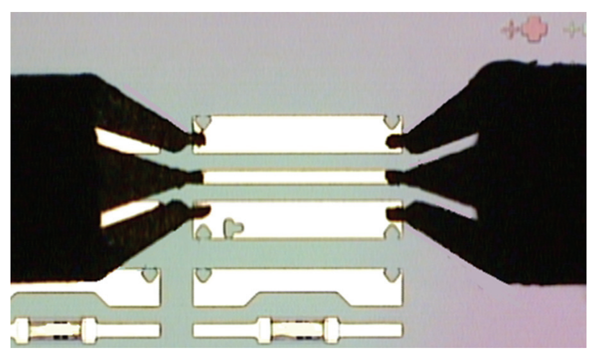


Figure 5: A Co-planar waveguide thru-line being probed

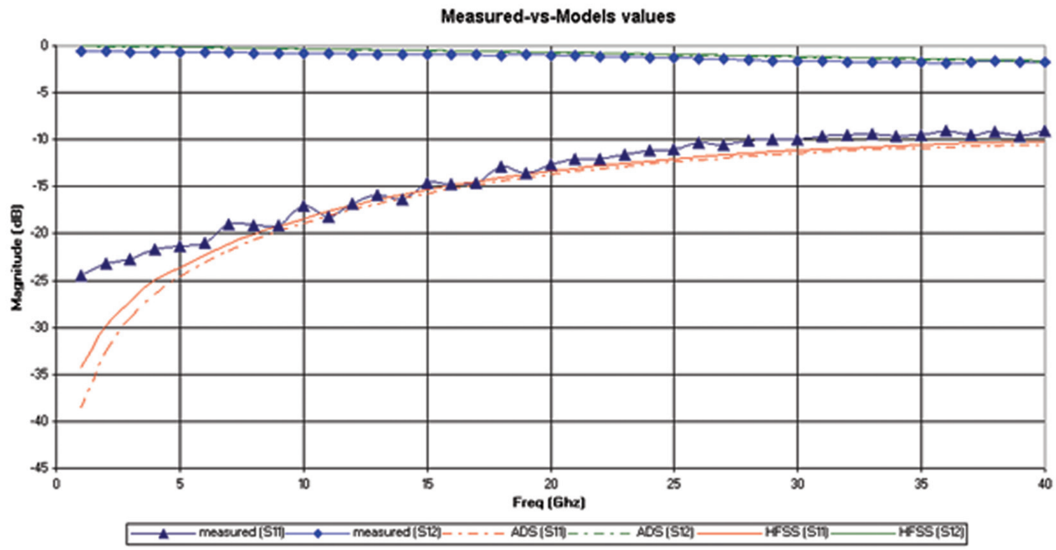


Figure 6: Comparison of measured and modeled data

Planned Future Work:

The lessons learned from this effort will be applied to the development of switches between 40-300 GHz. This technology is an important element for the proposed Cosmic Microwave Background - Polarization (CMBPOL) mission. Funding opportunities will be sought from RTOP and NASA Research Announcements (NRA).

Summary:

This project sought to increase Goddard's knowledge base on RF MEMS switches. Their application to scientific instrumentation had not been studied before. We strongly believe that this is a capability that will enable future, ambitious instruments like CMBPOL, which aims to detect the faint signals of polarization in the afterglow of the big bang, called the cosmic microwave background. This measurement will be for a generation or more the only way of determining, relatively directly, whether a postulated "inflationary phase" occurred early in the first fraction of a second of the big bang. This capability is not addressed by current industry projects. This technology will allow us to design instruments that otherwise would not be possible. Although we were not able to make a fully functional switch, we did learn the fabrication issues that affect these devices, and we were successful at testing basic structures up to 40 GHz. The fabrication process was, and remains, our major risk factor. At this point, however, we believe the risk can be mitigated by continued development and increasing our experience, as opposed to overcoming an inherent technical problem.

Ultra High-Density Printed Circuit Boards (PCB) with Embedded Passive Devices

Principal Investigator: Harry Shaw (Code 562)

Other Investigators: Arthur Ruitberg (563), Brandon Lee (562), Jeannette Plante (562), Donhang Liu (560) and Jong Kadesch (562) and at JPL: M.Underwood, G. Carr, C. Iwa, S. Kayali, D. Gerke, P. Zulueta

Initiation Year: FY 2003

FY 2003 Authorized Funding: $35,000

Actual or Expected Expenditure of FY 2003 Funding: In-house - $30,000

Status at End of FY 2003: To be continued into FY 2004

Expected Completion Date: December 2004

Purpose of the Investigation:

The goal of this investigation is to develop a smaller and lighter circuit board without sacrificing reliability, a key requirement for future NASA space missions that emphasize smaller, lighter satellites and components. We plan to accomplish this through the development of ultrahigh-density Printed Circuit Boards (PCBs) with embedded passive technologies. This would move components such as resistors and capacitors, which take up space, off the surface of the board and into the layering of the board itself. This would improve the size, performance, cost and reliability of PCBs. Space needed for power for a satellite's many components can add up, and thus miniaturization will lend itself to more compact spacecraft.

Accomplishments to Date:

We obtained two circuit designs to initiate this research activity. One is a 6V, 30W DC/DC converter design that was obtained from the Power Electronics Branch at Goddard. The other is a 5A, 40W DC/DC current source designed by the Jet Propulsion Laboratory (JPL). Pursuing these two designs in parallel provides good potential for direct portability to space applications. The Goddard circuit has not been flown; the JPL circuit has functional and flight heritage. This gives us the opportunity to demonstrate a variety of different embedded passive components while reducing project risk at the prototype stage. By collaborating with JPL, with its history of major involvement in advanced microelectronics development, we also hope to incorporate this knowledge base and accelerate the adoption of the technological advancements achieved in this DDF across Earth and Space Science Enterprises.

First, a bit of background: Embedding dielectric and resistive materials in special geometries inside the layers of laminated PCBs improves reliability by reducing the number of chip capacitors and resistors used and their associated solder joints. Performance is also enhanced because delay and losses in the connections between the capacitors and resistors and the integrated circuits are reduced through shortened path lengths and better heat transfer to the board from the resistors. Effective thermal management also increases system reliability, stabilizes performance and slows component aging.

Magnetic components are harder to miniaturize because the operation of a transformer, choke or inductor is directly related to the amount and type of ferrite material used. The coils, though, can be integrated more closely with the PCB and this will be demonstrated. Again, footprint, reliability and performance enhancement are the expected results. We must use advanced design tools and careful analysis in order to design and manufacture a successful circuit with embedded passives (three types). Research and coordinating with vendors is a necessary and significant part of the activity, because the PCB houses and the embedded passive material vendors are separate. The circuit used must be portable to a space application to demonstrate the validity of the research and to impose real flight hardware concerns onto the planning process. The assembly must be built and tested over flight conditions such as thermal vacuum and temperature extremes.

Concerning our "parallel" study of the Goddard and JPL circuit designs: Extensive analysis of the designs and the parts were done for two reasons. One was to convert radiation hard integrated circuits (ICs) to affordable and available commercial parts or EM-grade parts. The other was to find the candidates for resistor and capacitor embedding from the values needed. Modeling and analyses of the circuit subsections was done for both the Goodard and JPL designs to confirm that the IC replacements and embedded passives selected were correct. All parts and packaging outlines were identified prior to the board layout.

The Goddard converter circuit was divided into two subsections by functionality blocks. These two subsections are named the power stage and control stage. The circuit designer, Art Ruitberg, designed the embedded transformers in concert with the packaging engineer (Brandon Lee, Dynamic Range Corp) as the board was being laid out. Embedded passives will be added to this design in a later revision. The layout for both subsections is complete and is shown in figure 1 and figure 2. The board for the power block has been built and populated (figure 3) while the control stage board is currently being built. Upon receipt of the control board from the board manufacturer, these two boards will be mechanically assembled and connected through a wiring harness, and then delivered to the power group for electrical verification.

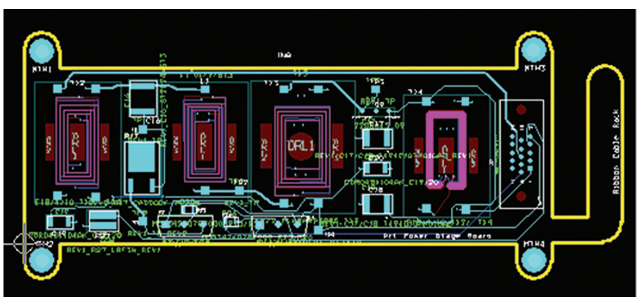


Figure 1. Layout view of Power Stage Block of the Goddard Converter

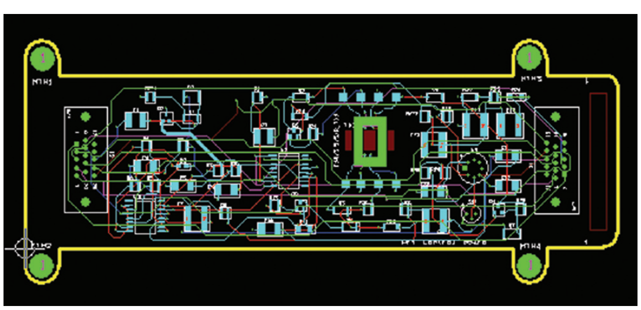


Figure 2. Layout view of Control Stage Block of the Goddard Converter

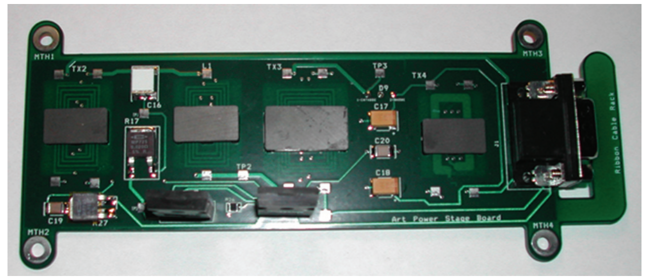


Figure 3. A view of Power Stage board of the GSFC Converter

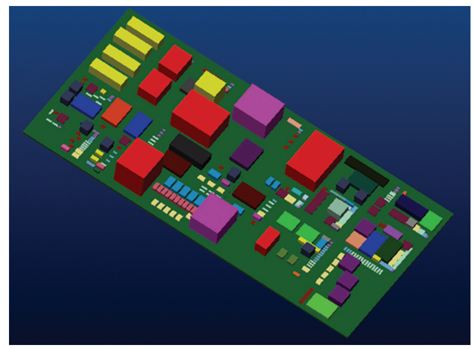


Figure 4. A view of CAD Modeling for the prototype JPL board (non-optimized)

For the JPL converter, a preliminary design review with JPL was conducted and resulted in a reduction of circuit complexity and a better understanding of the circuit, the critical packaging and layout constraints. Figure 4 shows a CAD model used to visualize the geometry-driving components of the system and the geometry resulting from the functional flow of the circuit and schematic, realized at the component level. All parts for the JPL boards have been ordered and most are in stock. Currently, the JPL board layout is in progress with packaging reviews done at the subsection level (there are five).

A novel method of embedding of magnetic components was reported by Yi E. Zhang, Seth R. Sanders and the Department of Electrical Engineering and Computer Sciences at the University of California, Berkeley through the IEEE in 1999. This method was researched including several conversations with the students' advisor, Dr. Sanders. This method embeds not only the windings but the core material as well. A sample of an embedded transformer using this method was provided to Goddard and analysis is being performed to enhance the mechanical and manufacturability properties of the device.

Planned Future Work:

Based upon successful electrical verification of the two sections of Goddard DC/DC converter design, including the embedded magnetics, we will combine and reevaluate the schematics for insertion of the embedded resistors and capacitors. We will also implement a miniaturized connector interface (if it is not replaced by terminal pins). We will conduct electrical characterization and packaging ruggedization on this second revision.

The layout for the first generation of the JPL DC/DC converter will be continued and completed with embedded passive resistors and capacitors. Prior to having the layouts built up as PCBs and then populated, we will conduct a critical design review with JPL. Assuming no large problems are found, we will build up the boards and perform electrical and temperature testing. We will use hand-wound magnetics for the first-generation JPL boards. Due to the sizes of the magnetics needed in the JPL design, we will attempt this novel method in revision 2 of the JPL circuit build. "Revision 1" will supply a good functional baseline with the embedded passives for the "Revision 2" build that will further miniaturize and include the embedded magnetics. The goal is to embed the majority of the passive components through internal board lamination or techniques to minimize the number of components soldered to the surfaces of the PCB.

Summary:

This project will be the first to bring advanced embedded magnetics, capacitor and resistor technology to a NASA design and the first to show the use of fully embedded magnetics in a space application. These technologies hold great potential for reducing power system circuits with no loss of reliability. For Goddard, this study will provide important data on the effectiveness and usefulness of embedded passives in this critical application. Circuits that are 100% portable to NASA missions are being used to demonstrate this technology. Good results during this R&D effort will quickly translate to flight-grade hardware. To succeed, the circuits that use embedded passives must operate at least as well as the original designs over a moderate temperature range and in a hard vacuum. Technical risks lie in the variation in performance of the embedded passives as compared to their surface-mount equivalents. Significantly different performance on the plus or minus side can prevent the circuit from behaving properly to the point of being destructive to itself and collateral circuitry. Storage components such as capacitors and magnetic devices (inductors and transformers) play important roles in converters both as sources of voltage and current during the internal duty cycle of the switch-mode converter and as sources of impedance into and out of the converter. Embedded magnetic cores undergo magneto-strictive effects that alter the effective component values and must be accounted for. Unexpected behavior or out-of-specification parameters can be the source of resonance and oscillations. The work to build prototype units is being done in a modular fashion in order to validate the circuits with embedded resistors and capacitors and then with the embedded magnetics to guard against designing in application-killing circuit behaviors.

Formation Control Experiments Inside the Space Station

Principal Investigator: J. Russell Carpenter (Code 595)

Co-Investigators: David Leisawitz (685), David Miller (MIT)

Initiation Year: FY 2002

Aggregate Amount of Funding Authorized in FY 2002: $35,000 (with Goddard funding of $40,000 for FY 2000 through 2001)

FY 2003 Authorized Funding: $30,000 (augmented with another $60,000 mid-year)

Actual or Expected Expenditure of FY 2003 Funding: $150,000 to Professor Miller at MIT (includes non-DDF funds).

Status of Investigation at End of FY 2003: Due to the Columbia accident, SPHERES has been delayed to no earlier than fall 2004; no additional funding is expected to be required at this time.

Expected Completion Date: early 2005

Purpose of Investigation:

The investigation provides groundwork for satellite formation flying -- that is, the ability for multiple satellites to orbit in precise position to each other, as is required in future missions such as the Laser Interferometer Space Antenna (LISA) and Magnetosphere MultiScale. Our investigation makes use of SPHERES (Synchronized Position Hold Engage Re-orient Experimental Satellites), a formation-flying spacecraft test bed prototype developed by Payload Systems Inc. and the Space Systems Laboratory in the Department of Aeronautics and Astronautics at the Massachusetts Institute of Technology. SPHERES provides a means for us to test the validity of metrology, formation flying and autonomy algorithms to coordinate the motion of multiple satellites in microgravity; and we can use SPHERES during reduced-gravity aircraft flights, in the Space Shuttle mid-deck, or on the ISS. Each SPHERES is indeed spherical, and in a microgravity environment they serve as “miniature” satellites -- analogous to remote-controlled model airplanes -- for us to assess the feasibility of formation flying. In this investigation, we are specifically adapting candidate-distributed spacecraft-control technologies developed at Goddard for validation via the SPHERES, and defining requirements, interface specifications, and preliminary designs for external payload interfaces with an end goal of performing formation control experiments onboard the International Space Station (ISS). For our contributions, Goddard will receive approximately one-eighth of the on-orbit resources of SPHERES during its time aboard the Space Station.

Accomplishments to Date:

MIT delivered a high-fidelity SPHERES simulator (V1.2) to Goddard that allowed us to begin integrating our algorithms. Goddard algorithms have been tested with SPHERES on the KC-135 zero-gravity aircraft as well as the MIT air-bearing test bed. Two SPHERES, five beacons and mounts, two laptop transmitters, 24 battery packs, 74 tanks (26 originally sent to Kennedy Space Center for launch on STS–114 and STS–115 and 48 sent for 13P launch) have been delivered to Johnson Space Center. On November 11, 2003, Commander Mike Foale performed a Beacon/Beacon Tester experiment onboard the ISS that provided information about infrared interference environment onboard ISS for future experiments.

Figure 1. Prototype SPHERES on NASA Zero-Gravity Aircraft

Planned Future Work:

Shuttle missions have been delayed. Our original plan follows: In January 2004, we were to launch one SPHERES, a laptop transmitter, two battery packs and four tanks on Progress 13P, 14P, or 15P (Russian rockets servicing the ISS) should space become available. In September 2004, after the STS 114 mission, we were expecting to have two SPHERES, one laptop transmitter, five beacons and mounts, and consumables for three test sessions onboard the ISS. Then, by STS 115 mission, the rest of the consumables would be onboard the ISS (96 tanks and 48 battery packs).

Summary:

SPHERES provides an innovative three-dimensional microgravity environment test bed that, when fully successful, will allow Goddard to validate metrology, formation flying, and autonomy algorithms for formation flying. Such knowledge is critical in designing and building future space-based missions calling for precision flying, such as LISA and Magnetosphere MultiScale. SPHERES will be among the first science payloads launched to the ISS as part of NASA's post-Columbia return to Shuttle flights.

A Colloidal MEMS Thruster

Principal Investigator: Eric Cardiff (Code 597)

Co-Investigators: Brian Jamieson (553), Peter Norgaard (intern from University of Washington), Ariane Chepko (intern from Purdue University)

Initiation Year: FY 2003

FY 2003 Authorized Funding: $25,000

Actual or Expected Expenditure of FY 2003 Funding: $6,000 for wafer fabrication; $3,000 for software; $2,500 for data acquisition computer; $10,000 for oscilloscope obligated; $1,000 for vacuum tank supplies; and an additional $2,500 expected for vacuum tank supplies.

Status of Investigation at End of FY 2003: To be continued in FY 2004 with remaining funds and additional DDF funding ($36,000).

Expected Completion Date: December 2004

Purpose of Investigation:

The goal of this project is to design a thruster with a thrust range from 1 micro-Newton (μN) to 100 milli-Newton (mN) using Micro-Electro-Mechanical Systems (MEMS) methods. Precision propulsion is needed for future formation-flying satellite missions such as such as the Laser Interferometer Space Antenna (LISA), with instruments that will often need to be positioned remotely to nanometer accuracy. Our device works via electrostatic propulsion. Developing the thruster as a MEMS device on a silicon wafer allows many arrays to be manufactured cheaply and rapidly, and will allow more devices to be used, thereby extending the range of thrust that can be produced. This means that one single, small propulsion system can cover a wide range of thrust needs that traditionally would require several propulsion units, reducing the mass of propulsion systems by a factor of ten. Our systems would also require less propellant. The primary challenge in designing a MEMS electric thruster is the development of insulation between the accelerating electrodes and the emitter.

Accomplishments to Date:

We have developed a process to manufacture the MEMS thrusters, and we have fabricated several prototypes. An example of the prototype device showing the silicon dioxide lattice structure is shown in figure 1. We solved the primary challenge of the insulation technique by using a novel MEMS fabrication technique to increase the thickness of the silicon dioxide. We etched a high aspect-ratio lattice structure into the silicon thruster substrate using a deep reactive ion etcher (DRIE). This structure was then thermally oxidized to produce an insulating spacer an order of magnitude thicker than that which can be achieved with the thermal oxidation of silicon alone. Using this technique, the electrical breakdown voltage was increased by more than a factor of 10 to over 3 kV.

We investigated the electrical breakdown of the insulation as a function of pressure in a vacuum tank (figure 1). We also investigated the failure modes of the insulation, and we identified one mode to be buckling on the insulation columns due to over heating.

We began a modeling effort, in addition to the design effort, to examine the formation of the Taylor cone. The Taylor cone is formed by the interaction of the electrostatic field and the surface tension. Thrust is produced at the tip of the Taylor cone where the fluid becomes unstable and breaks down into droplets, which are accelerated away from the emitter by the electrostatic field. A schematic of the Taylor cone and colloidal thruster is shown in figure 2. The model has been successfully used to examine the early stages of the Taylor cone growth, although the discontinuity of the droplet formation at the tip of the cone remains to be solved.

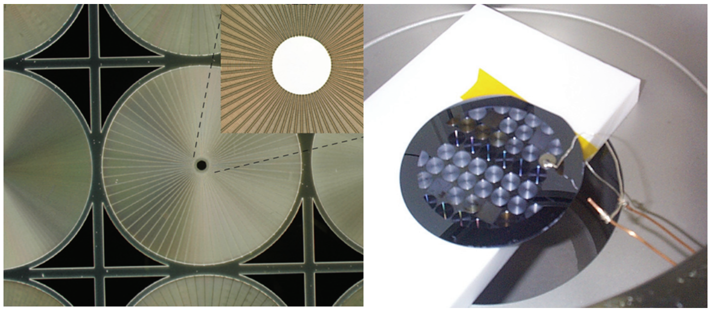


Figure 1: Image of the colloidal thruster emitter with a close-up of the insulation (left) and the setup for the insulation testing in vacuum (right).

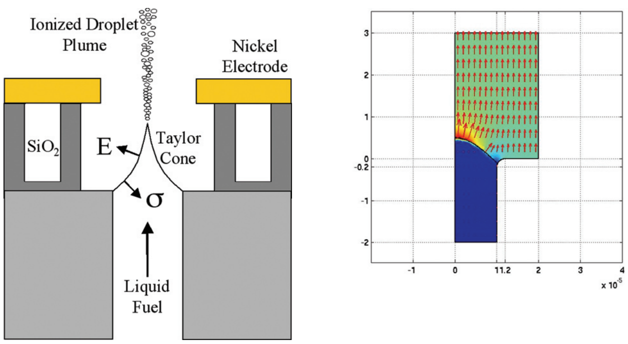


Figure 2: Schematic of the Taylor cone and the MEMS colloidal thruster (left) and results from a computer simulation of the Taylor cone formation showing the electrostatic field and the fluid density (right).

Planned Future Work:

Based upon these promising results, the next phase of the research will be to test the operational characteristics (thrust and specific impulse) of the thruster array. This will be accomplished using a Time-of-Flight technique to measure the velocity of the droplets as they leave the emitter. We will also use a new optical in-vacuum microscope to examine the dimensions of the Taylor cone for validation of the computational model. We plan to present the preliminary results of this research at the AIAA JPC in July 2004.

Summary:

Significant progress has been made in developing a MEMS colloidal thruster with a wide thrust range. Such a device could decrease the propulsion system mass of large formation-flight missions by a factor of 10. This would benefit Goddard in its ability to participate in the development of these types of ambition space-based missions, such as LISA, the Micro-Arcsecond X-ray Imaging Mission (MAXIM) and the Terrestrial Planet Finder (TPF). A thrust range of 1 μN to 100 mN must be developed to produce a significant mass benefit. The principal accomplishment of this research has been a novel MEMS fabrication technique for electrode insulation. The insulation was the main technical risk. Attempts by other researchers to develop this type of thruster all failed because of problems with electrical breakdown of the insulation. The propellant feed system remains a significant technical risk, and this must be solved to demonstrate the operation of the thruster over the entire thrust range -- our criteria of success.

Ceramic Substrates for Advanced Monopropellant Decomposition

Principal Investigator: Mark Underdown (Code 597)

Co-Investigators: Allan Cohen (597)

Initiation Year: FY 2003

FY 2003 Authorized Funding: $24,000

Actual or Expected Expenditure of FY 2003 Funding: $2,000 for Argonide; $7,500 for CM Furnace; $2,000 for mechanical fabrication

Status of Investigation at End of FY 2003: To be continued in FY 2004 with unspent DDF funding

Expected Completion Date: June 2004

Purpose of Investigation:

The main goal of this investigation is to design and fabricate ceramic substrates that can function in a high-temperature environment. These substrates would be used with a safer, more environmentally benign fuel that needs to be at high temperatures in order to serve as a high-performance propellant on multiyear satellite missions. The common propellant used on upwards of 99% of satellite missions is hydrazine, an efficient fuel but a cancer-causing agent that is costly and hard to handle. An alternative propellant is hydroxylamine nitrate, or HAN, a "green" fuel that is about half the cost of hydrazine and poses fewer risks to workers handling the fuel. Also, unlike the high-performance liquid oxygen/nitrogen fuel used on the Space Shuttle, HAN doesn't require bulky cryogenic storage and is thus ideal for multiyear missions. However, to reach a high-performance level, HAN must attain high temperatures -- temperatures that essentially melt some materials in current fuel-combustion devices. Ceramics are needed to withstand this heat. Our investigation involves creating ceramic substrates by sintering (a type of molding) nano-powder materials, a new and unique option. The goal of the second phase is to evaluate the materials in a prototype catalyst bed reactor. The catalyst lowers the energy required to break down the liquid propellant into smaller gas molecules, which would then be pushed through the nozzle to propel the spacecraft.

Accomplishments to Date:

We obtained nanopowder-sized materials as well as various forms of alumina and zirconia. We performed surface area measurements on candidate materials. We added filler materials in the form of fine particles of carbon to make a more porous substrate. Early results indicate that zirconium oxide and carbon filler materials can be sintered into a relatively porous substrate, which is what is needed. The filler materials were completely oxidized and removed during the high-temperature sintering process. The resulting material could be crushed into rough catalyst substrates. Once sintered into substrate form, these materials should resist further densification during thruster operation.

In parallel, we designed and fabricated a workhorse HAN reactor with special attention to the 1700 C temperature of the HAN combustion. The reactor made extensive use of materials such as molybdenum and ceramics (see photos). Along with the reactor, a propellant feed system was designed. Testing of the propellant feed system is underway. We are in the process of finalizing the data acquisition system and thermocouple sensor locations on the reactor.

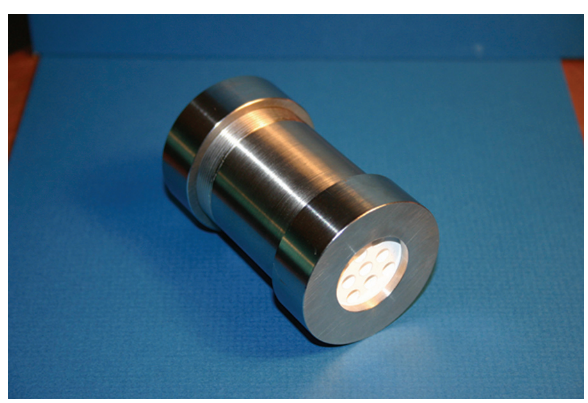


Figure 1. Photo of Test Reactor (inlet tube not installed)

Planned Future Work:

Based on the early results, we hope to test the materials in the workhorse reactor under flow of propellant. We will perform surface area measurements on the catalyst materials before and after exposure to the propellant. Acceptability of the material will be based on this data as well as evidence of (or lack there of) destructive sintering within the inner layers of catalyst during thruster operation. The catalyst lowers the energy required to break down the liquid propellant into smaller gas molecules, such as the hydrazine reaction: $2N_2H_4$ liquid ----> $2NH_3 + H_2 + N_2$.

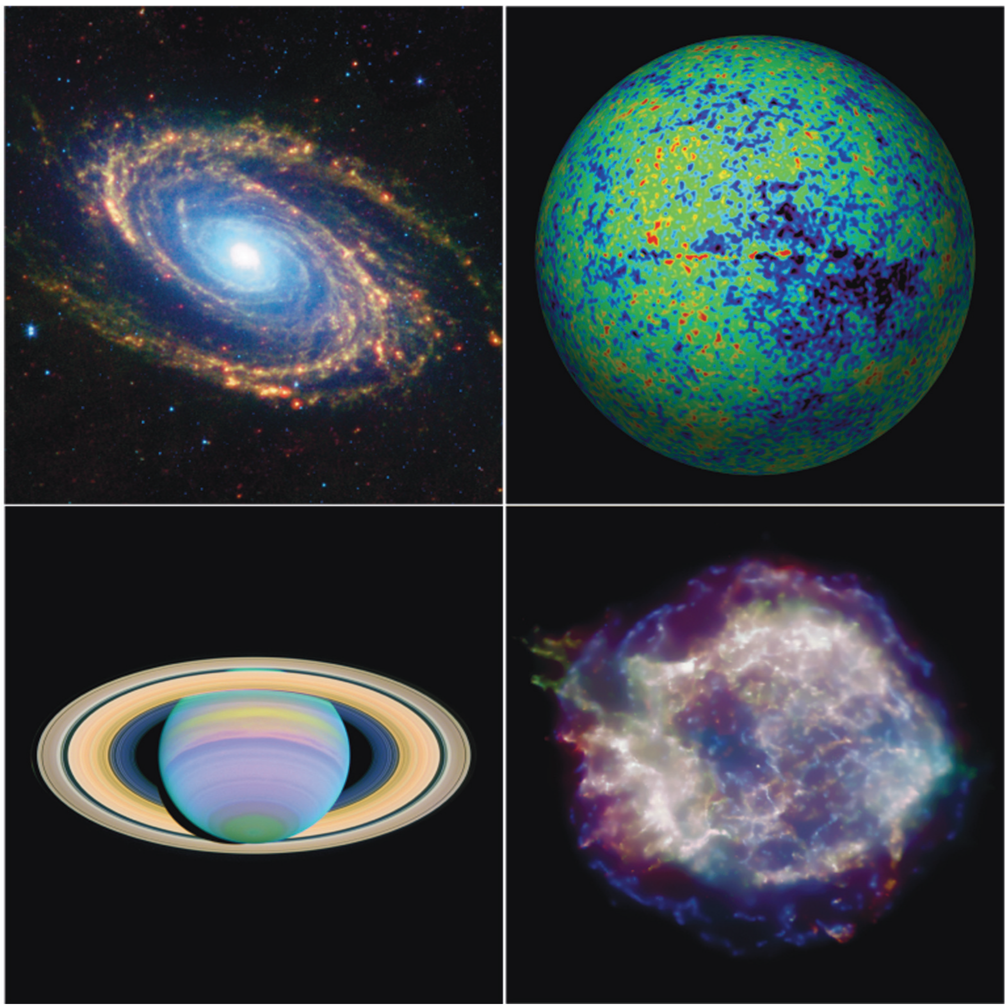
Figure 2. Disassembled to show construction and High Temperature Materials

Figure 3. Micromeritics BET Surface Area Analyzer

Summary:

Our use of nanotechnology materials represents an important new approach to create ceramic substrates that can withstand high temperatures. These materials provide the advantage of high surface area for performance and lower sintering temperature (similar to forging) for ease in manufacture. These materials also offer stability at high temperature and resistance to oxidation required by HAN propulsion systems, which are safer and less expensive than hydrazine propulsion systems now in use. Goddard and NASA can benefit in numerous ways, for a HAN could be used for SMEX, MIDEX and ST5-size missions. The cost, mass and volume savings of a HAN system over a hydrazine system for small spacecraft on a tight budget is significant. For a proposed mission with a total mass of 580 kg, a HAN system could reduce tank mass by 26%, fuel mass by 19%, and tank volume by 34%. Our criterion of success is that our catalyst, which lowers the energy required to break down the liquid propellant into smaller gas molecules, completely decomposes the propellant without being destroyed or losing surface area. The catalyst development is a crucial step in realizing HAN systems for small satellites. Although the commercially available product Shell 405 performs well as a catalyst and has been incorporated into a thruster design, it is quickly destroyed by the HAN propellant. A different catalyst-support system is needed. The nanofiber alumina holds promise as an ideal catalyst support material. Finding a suitable catalyst is our greatest technological hurdle at this point.

Space Sciences Directorate



Development of Fused Silica Fibers for use in LISA Torsion Pendulum Apparatus

Principal Investigator: Jordan Camp (Code 661)

Co-Investigators: Kenji Numata (661) and John Blackwood (541)

Initiation Year: FY 2003

FY 2003 Authorized Funding: $95,000

Actual or Expected Expenditure of FY 2003 Funding: Machining costs, $25,000; vacuum pump, $15,000; lasers and optics, $15,000; fused silica fiber coating and manufacturing facility, $40,000

Status of Investigation at End of FY 2003: To be continued in FY 2004.

Expected Completion Date: Nov. 2004

Purpose of the Investigation:

We are attempting to markedly improve the sensitivity of a torsion pendulum, an ultra-sensitive apparatus used to monitor minute force and movement. Such a pendulum is needed to test on the ground instrumentation planned for the Laser Interferometer Space Antenna (LISA), a three-satellite mission that will detect gravitational radiation, or ripples in spacetime. These waves, predicted by Einstein but not yet detected, alter the space between objects as far apart as the Earth and the Moon by less than the width of an atom. Such waves would alter the distance between free-falling test masses on the LISA satellites. The torsion pendulum, an instrument that converts applied force to rotation, is the only device that has sufficient sensitivity to measure acceleration noise levels - that is, the background force on a test mass - relevant to LISA but on the ground. The pendulum is in essence a test mass suspended by a fiber, simulating the zero-gravity environment of space. The torsion pendulum sensitivity is limited by mechanical loss (analogous to friction) in its suspension fiber. Current torsion pendula use tungsten fibers, which provide a sensitivity limit about 100 times worse than the LISA requirement of 10^{-15} Newton (a unit of force) over a 1,000-second timescale. We are developing fused silica suspension fibers for the torsion pendulum. Fused silica has mechanical loss up to 10,000 times lower than tungsten, leading to a possible noise limit for the pendulum close to the full LISA requirement.

Accomplishments to Date:

At the onset of this investigation, we first addressed the immediate problem with fused silica: It is an insulator, leading to pendulum noise from charge buildup. Thus, fused silica fibers must be coated with a conductive material before they can be used in a pendulum. The coating, however, must be such that it doesn't spoil the low-loss property of the fused silica. The PI of this investigation had previous experience with ultra-thin conductive germanium-gold (Ge-Au) coatings that appeared to be a good possibility for this coating. This investigation, then, was undertaken to work out the problems associated with the production of low-loss, coated fused silica fibers to be used in a full-sensitivity LISA torsion pendulum.

Kenji Numata, an NRC postdoc who is a leading expert in loss mechanisms in fused silica, initiated this work by traveling to the University of Washington, a leading U.S. center of torsion pendulum research. Working with Jens Gundlach, Numata applied about a 5-nanometer-thick Ge-Au coating to a 100-micron-thick, 30-centimeter-long fused silica fiber in a special coating chamber. They then hung the fiber in a torsion pendulum, excited its rotational motion, and by watching its decay, measured its mechanical quality factor (Q) to determine the fiber loss. The results are shown in figure 1. The measured fiber Q after coating is about 100,000, about 100 times higher than possible with tungsten. In figure 2 we show a comparison of the expected force noise from torsion pendula with tungsten (Q=1,000), and a fused silica fiber (Q=100,000). We believe that much higher Qs are possible with iteration of the coating design.

Planned Future Work:

Based upon these exciting 2003 DDF results, the next phase of the research will focus on drawing fused silica fibers at Goddard, coating them, and then measuring their Qs. The steps planned are (1) the construction of a torsion pendulum to measure other coated fused silica fibers, (2) the modification of a coating chamber in the Goddard material science branch to allow fiber coating, and (3) the development of a facility in code 541 to manufacture the thin fibers. Step 1 has been completed; step 2 has begun; and step 3 will start sometime in early 2004.

There will be a significant amount of activity involved in iterating the fiber and coating design to achieve maximum Q. We believe it should be possible to produce coated fibers with Qs greater than one million, and possibly as high as 10 million. A truly exciting outcome of this research would be using the developed silica fiber to build a torsion pendulum research instrument at new levels of sensitivity, here at Goddard.

Summary:

This project's innovative feature is the use of coated, conductive, ultra-low-loss fused silica as a suspension wire for a torsion pendulum. Although torsion pendula have been in use for many years to measure very small forces, they have never employed fused silica fibers. This possibility would allow a large increase in pendulum force sensitivity, for other physics studies as well as for LISA. A torsion pendulum capable of reaching the acceleration noise requirement would have great benefits for the LISA mission, allowing full acceleration noise tests of LISA instrumentation on the ground. The possibility of constructing such a pendulum here at Goddard would help to establish Goddard as a serious player in this crucial area of LISA research. This would be important in supporting Goddard's role in LISA's integration and testing. Our criterion for success is the development of conductive fused silica fibers with Q (the mechanical quality factor) greater than 1,000. We have already achieved this for 100-micron fibers with a measured Q of 100,000. We wish to extend this result to much higher Q. The technical risk factor is the effect of the germanium-gold coating on the Q of the fiber. It was unknown if the coating was compatible with high Q, but we have shown this to be possible. It also remains unknown how high a Q is possible with modification of the coating design. This investigation was formerly called "Development of Environmental Control Systems for Integration and Test of LISA".

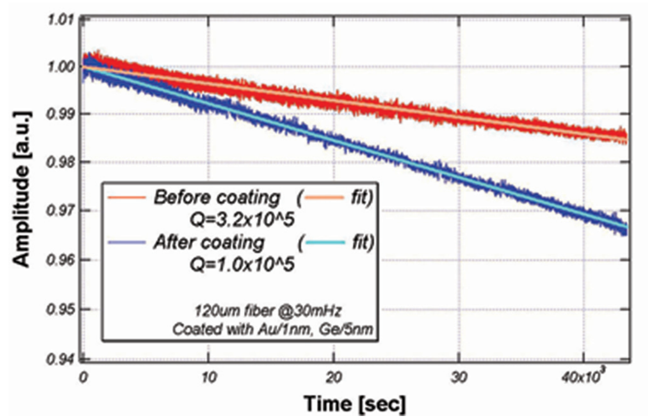


Figure 1: Amplitude decay of torsion pendulum using coated and uncoated fused silica fiber.

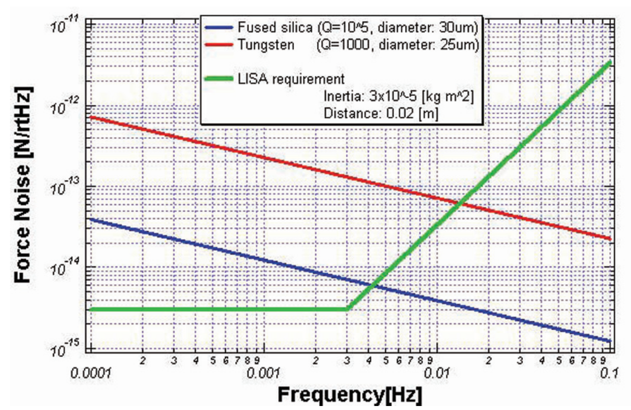


Figure 2. Torsion pendulum acceleration noise sensitivity with tungsten and fused silica fibers. Acceleration noise requirement rises at high frequency due to shot noise, a statistical noise term related to variation in the number of photons collected during the measurement. Fewer photons are collected, and the *relative* variation in the number of collected photons increases.

Thick Format Dichroic Mirror

Principal Investigator: Alan Kogut (code 685)

Co-Investigators: Edward Wollack (685)

Initiation Year: FY 2003

FY 2003 Authorized Funding: $65,000

Actual or Expected Expenditure of FY 2003 Funding: Lesmo Machinery, $2,000; MWS Wire, $8,000; California Fine Wire, $5,000; Science Systems and Application, $35,000; miscellaneous machining charges, $15,000

Status of Investigation at End of FY 2003: Transition to RTOP funding (Code R)

Expected Completion Date: September 2004

Purpose of the Investigation:

The purpose of this investigation is to develop a low-cost method to fabricate thick perforated plates for use as filters in telescopes detecting microwave and infrared radiation. The perforations -- essentially tiny holes 100 to 150 microns in diameter -- would selectively split incident light into two "colors", with wavelengths smaller than the hole diameter transmitted through the plate to a detector and wavelengths larger than the hole diameter reflected away. The current state of the art for such filters uses mechanical drills to bore an array of holes in a metal plate. Mechanical drilling has several limitations. The smallest practical hole diameter is 1,000 microns (one millimeter), which is suitable for filtering long-wavelength microwaves but not radiation at shorter (infrared) wavelengths. Mechanical drilling also places limits on the thickness of the plate, the angle of the hole, and how tightly spaced the holes can be, which together limit the efficiency of the filter. We are investigating methods that use chemical etching to produce fine holes in thick metal plates. This could lead to a telescope system with a series of dichroic, or beam-splitting, filters of differing perforations that -- through a process of transmission and reflection -- could selectively filter and direct light to detectors much like a vending machine separates coins of different diameters. This would result in increased optical performance with fewer telescope parts needed to reflect and redirect light. And once automated, this chemical etching process could also reduce the cost of creating such filters.

Accomplishments to Date:

We have successfully built thick perforated plates using chemical etching, demonstrating the basic feasibility of chemical methods. For testing purposes, we created 800-micron perforations. We solder a long thick bundle of copper-clad aluminum wire (a commercially available product) to produce an array of uniform aluminum cylinders surrounded by a "sea" of copper and solder (figure 1). The resulting composite can be cut at an angle and machined into any desired shape, including tilted planes or convergent mirrors. Chemical etching then dissolves the aluminum, leaving an array of cylindrical holes in a conductive medium. Since machining is done before etching, the remaining surface is optically smooth. Light with wavelength larger than 1.7 times the hole diameter is reflected, while shorter wavelengths are transmitted. We have built a prototype dichroic blank that is 2.5 centimeters in diameter and 10 centimeters long using hand assembly of the wires in a copper mount. Figure 2 shows the etched surface. Larger units for far-infrared photometers require mechanical wire preparation. We have designed a jig to coat the wires in solder, straighten them, cut them to length, and deposit the cut wires in a copper-mounting bracket. Prototype testing of the jig is underway.

Planned Future Work:

Our 2003 DDF effort demonstrates the basic utility of chemical methods for the production of dichroic mirrors. We have a process that works, and we will next attempt to automate the process. Our hand-assembly enables us to produce durable arrays with up to 1,000 wires. We will transition the project to RTOP funding (Code R) to further automate the assembly process in order to produce larger arrays (10,000 to 1,000,000 wires) suitable for far-infared photometers in Earth or Space science.

Figure 1. Un-etched mirror blank produced by soldering long straight sections of copper-clad aluminum wire. Thick blanks can be cut at an angle (as in this example) or machined to form convergent mirrors while still keeping the wires parallel to the optical axis (vertical in this example). Chemical etching then removes the aluminum wires, leaving an array of cylindrical holes in a metallic substrate.

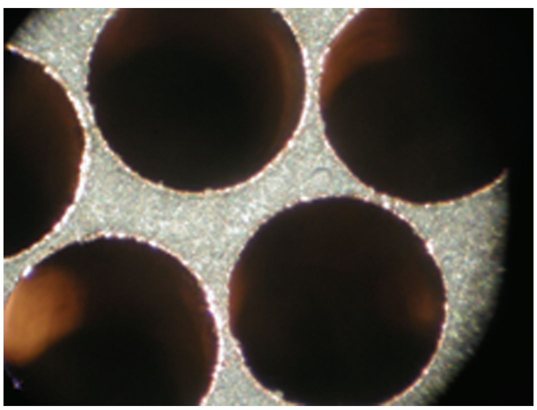


Figure 2. Close up of etched plate showing copper "tubes" remaining after the aluminum wire is etched away. Chemical etching can produce large arrays at low cost.

Summary:

This project is developing a cheaper, more reliable method to fabricate perforated plates for dichroic optics, which could be used on future microwave and infrared space-based science missions. This would place Goddard in a favorable position in proposing and building such missions. We use a unique approach: chemical etching instead of mechanical drilling. Combining thick plates and holes produced by chemical etching allows for machining the plate into complex surfaces without compromising optical performance. Our criterion for success is to construct a filter of enough mechanical integrity to withstand launch vibrations, upwards of 10 G. The largest uncertainty, and thus one technical hurdle, is this mechanical stability of the etched structure. But a proof-of-principle prototype demonstrates the utility of chemical etching for large dichroic mirrors.

Active Matrix Pixel Proportional Counter for X-ray Polarimetry

Principal Investigator: Rob Petre (code 662)

Co-Investigators: Keith Jahoda (662), Kevin Black (Forbin Scientific), Phil Deines-Jones (USRA), Bob Street (Palo Alto Research Center)

Initiation Year: FY2003

FY 2003 Authorized Funding: $65,000

Actual or Expected Expenditure of FY 2003 Funding: In-house, $20,000; Palo Alto Research Center, $15,000; Forbin Scientific, $15,000; USRA, $15,000

Status of Investigation at End of FY 2003: Completed; basis for the Advanced X-ray Polarimeter Small Explorer proposal, selected for technology development funding.

Expected Completion Date: completed

Purpose of Investigation:

Our goal was to develop a new type of polarimeter instrument for future satellites to measure X-ray polarization. Polarization (oriented magnetic and electric fields of light waves) provides information not directly available from more common types of imaging and spectroscopy typical of most NASA missions. Light becomes polarized in the presence of magnetic fields or when it scatters off of cosmic dust or even the hood of a car. An X-ray polarimeter, such as the one we are building, could measure the geometry of "the accretion disk" of matter swirling into a black hole and the magnetic field strengths of a variety of exotic objects. Our polarimeter uses a finely segmented pixel gas proportional counter with sufficient area to cover the focal plane of an X-ray telescope. X rays enter the instrument, react with the gas, and leave a trail of ionization, from which we can determine the energy and polarization of the X rays that left the trail. Our photoelectric polarimeter uses a pair of gas electron multipliers (GEMs) above a thin film transistor (TFT) array. An incident polarized X-ray photon first enters the detector chamber and excites an electron which then carries a "memory" of the photon's polarization. The electron ionizes other electrons that drift into the GEM multipliers before being deposited on the TFT. The end result -- a 100-fold increase in polarization sensitivity per collecting area over standard techniques - will allow for sensitive polarization measurements on a small satellite, such as a Small Explorer (SMEX) mission.

Accomplishments to Date:

During this DDF investigation, we constructed a double-GEM with an amorphous-silicon active-matrix readout. The GEMs were fabricated at Goddard; the amorphous-silicon thin-film transistor array readout (such as those used in flat-panel displays and solid-state medical imagers) was developed by the Palo Alto Research Center. (figure 1) Both detector and readout pixels were on 100 micron spacing. The GEMs were 1 cm^2, while the TFT array was 25 cm^2. (figure 2) We recorded photoelectron track images from 4.5, 6.0, and 20 keV X rays and made measurements with polarized X rays at 4.5 keV. Figures 3 and 4 show example track images.

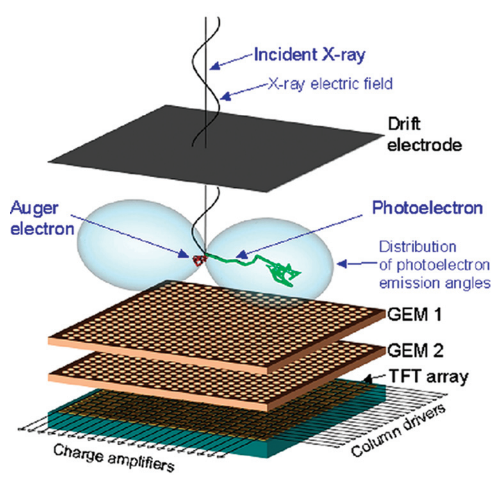


Figure 1. Schematic diagram of detector geometry used in measurements. The $\sin^2\theta\cos 2\phi$ distribution of photoelectron emission is projected onto the detector plane and observed as $\cos 2\phi$

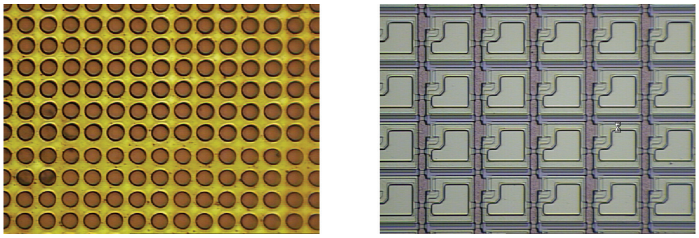


Figure 2. Optical microscope photographs of a Goddard gas electron multiplier (left) and a standard PARC TFT test array (right).

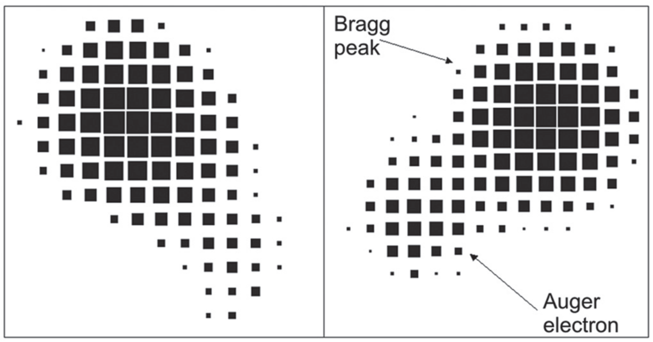


Figure 3. Track images from 6 keV X-rays. The boxes represent pixels on 100-micron spacing. The size of the box is proportional to the charge collected in that pixel. Both the Auger and photoelectrons can be seen.* The Auger electron is created at the X-ray interaction point with a characteristic energy (870 eV in this case). The ionization created by the photoelectron increases as it loses energy, so that most of the ionization is deposited near the end of its path, a point called the Bragg peak.

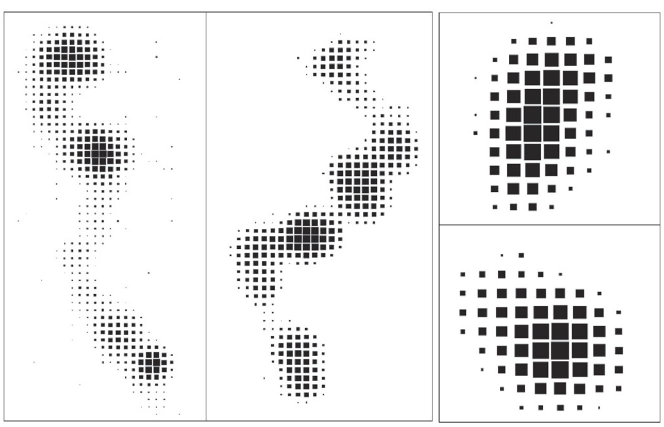


Figure 4. (Left) Track images from 20 keV X-rays. The Auger/interaction point can still be identified among more hard interactions of the photoelectron. (Right) Track images from 4.5 keV X-rays. The Auger and photoelectron can no longer be distinguished, but the tracks still have a discernable direction.

Measurements of polarization sensitivity were made at 4.5 keV. We created polarized X rays by scattering them at 90 degrees from a silicon crystal. The crystal, and hence the plane of polarization, could be rotated with respect to the detector, as shown in Figure 5. We analyzed the data by reconstructing the emission angle of each of the recorded photoelectrons, then forming histograms of those angles. The histograms were then fit to the expected $A + B \cos^2\theta$ form. The results are shown in Table 1. The data fit the expected functional form with an average modulation of 33%. Modulation is defined as the observed fractional polarization for 100% polarized X-rays.

The results were published in Nuclear Instruments and Methods A (Nucl. Instr. and Meth. A 513 (2003) 639-643) and presented at the annual meeting of the International Society for Optical Engineering (SPIE). This work also formed the basis for a GSFC-led proposal, the Advanced X-ray Polarimeter, to the NASA Explorer program. That proposal was selected for technology development funding.

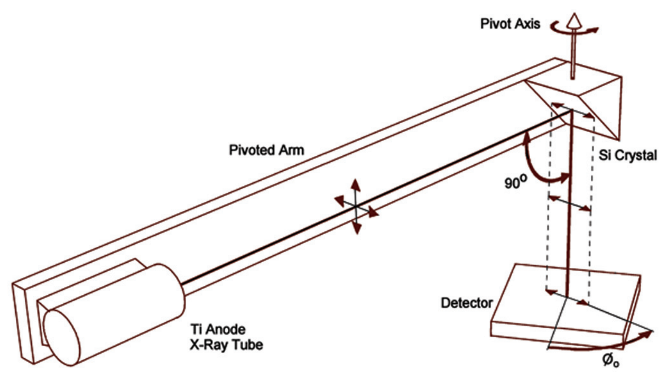


Figure 5. Experimental set-up for polarization measurements.

* The photo-electron is knocked loose by the incoming photon. The Auger electron is a secondary electron that is set free from an outer shell to conserve energy as another electron fills an inner shell vacated by the photo-electron.

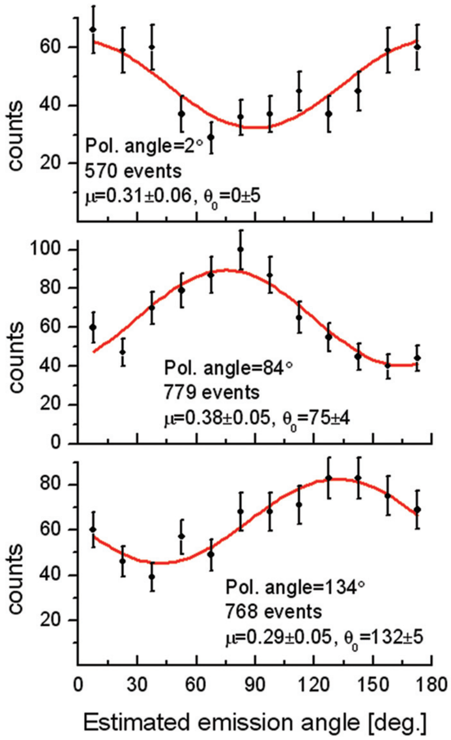


Figure 6. Histograms of reconstructed photoelectron emission angles (data points) and fit to the expected functional form (curve).

Planned Future Work:

Future work will focus on enhancing instrument performance. Key areas for improvement are quantum efficiency and charge collection efficiency, as well as modifications to the readout electronics to make it more suitable for astronomical polarimeters.

Summary:

This is the first time a proportional counter has been directly read out with an active matrix device. It is also the first demonstration of a practical astronomical photoelectric X-ray polarimeter. The results of this project formed the basis for a Goddard-led proposal, the Advanced X-ray Polarimeter, to the NASA Explorer program, which was selected for technology development. Despite a wealth of theoretical literature, astronomical X-ray polarimetry has not fulfilled its promise because of the low sensitivity of polarimeters in the 2-10 keV band. This project demonstrated a polarimeter with orders-of-magnitude more sensitivity than previously possible with a technology suitable for an astronomical X-ray telescope. The goals of this project were to demonstrate a high-resolution active-matrix pixel proportional counter and to use that detector to demonstrate photo-electron tracking. Demonstration of polarization sensitivity exceeded the goals. Charge collection in gas from a proportional counter on an active matrix array had never been demonstrated previously and could have been too inefficient or been subject to too much cross-talk for effective imaging. It was also unknown if the thin-film transistors would survive in a proportional counter environment.

	Fit Parameters	
Polarization Angle	μ	ϕ
2	0.30 ± 0.06	0 ± 5
84	0.38 ± 0.05	75 ± 4
134	0.29 ± 0.05	132 ± 5

Table 1. Fit results to reconstructed emission angles. Stated errors are one standard deviation. The μ symbol represents modulation: $\mu = (A-B)/(A-B)$, where A and B are fit parameters. The number of counts shown in figure 6, N, equals $A+B\ \mathrm{Cos}^2\ (\theta-\phi.)$

Design and Test of an Innovative Calorimeter for the Study of High-Energy Cosmic Rays

Principal Investigator: John Mitchell (code 661)

Co-Investigators: Alexander Moiseev (661) and Robert Stretimatter (661)

Initiation Year: FY 2003

FY 2003 Authorized Funding: $62,000

Actual or Expected Expenditure of FY 2003 Funding: $25,000 for in-house design, fabrication and testing; $10,000 for Hamamatsu (photodiodes); $20,000 for Proteus/ELJEN (scintillator); $4,000 for IDEAS (ASICS); and $3,000 for electronic components

Status of Investigation at End of FY 2003: To be continued in FY 2004 with funds remaining from FY 2003.

Expected Completion Date: November 2004

Purpose of the Investigation:

The goal of this investigation is to develop a very mass-efficient calorimetric detector to study cosmic rays at energies above 10^{12} electronvolts (eV). Cosmic rays are atomic and subatomic particles moving close to light speed. The precise origin of cosmic rays above 10^{12} eV remains a mystery. The most practical method of measuring the energy of such a cosmic ray (typically protons or helium nuclei) is to allow the particle energy to be dissipated through a cascade of interactions in a massive absorber and to measure the energy deposited. The instrumented absorber then acts as a "calorimeter." Envision a box in which a cosmic ray enters the lid and travels through a series of thin, parallel absorption layers. This simple, traditional "flat" calorimeter design is appropriate for human-made particle accelerators where the direction of the particle is known. In space, cosmic rays come from all directions. Thus, such flat designs cannot measure the energies of most of the cosmic rays that enter the side of the detector. We are developing an omni-directional "cubic" calorimeter design that allows particles to arrive from any direction. This would be approximately three times more efficient (in terms of collecting power) compared to flat calorimeters of the same mass. As a bonus, it may be able to discern cosmic-ray electrons from cosmic-ray protons, which has been difficult in the past. Flat calorimeters have been tested extensively at accelerator facilities and are clearly mature enough to be considered for flight instruments. The main objective of our work is to bring similar credibility to cubic designs by design optimization using Monte-Carlo computer simulations and then by testing a prototype at a particle accelerator facility.

Accomplishments to Date:

The award for this project was made shortly before the freeze of the Goddard financial system and also too late to construct a prototype calorimeter for an August 2003 test time that we had been allocated at the CERN SPS (Super Proton Synchrotron) accelerator in Europe. However, great progress was made in developing the test plan and optimizing the design through extensive Monte-Carlo simulations using the CERN GEANT 3 package.

Cosmic rays are essentially isotropic, except as obscured by the Earth, and maximum efficiency is achieved by a calorimeter that will measure cosmic rays coming from above and from all sides of the instrument. We have shown previously (Moiseev et al., Proc. 27th ICRC, Hamburg, 2001) that the geometric factor of the cubic calorimeter -- that is, the space available for collection and measurement -- is about three times larger than that of a flat calorimeter of the same mass. This improvement can be used to increase the statistics obtained from a mission or to decrease the cost by reducing the flight duration or the instrument mass.

Our studies indicate that for mass efficiency the optimal cubic calorimeter should use materials with mean atomic number near that of iron, while for the flat design heavy materials (lead, tungsten) are superior. An ideal cubic calorimeter would be made up of small detector elements distributed throughout the volume. However, our studies also indicate that this can be approximated using scintillator bars spanning the width of the calorimeter. If successive layers of rods are rotated by 90 degrees, as shown in schematic form in figure 1, a full three-dimensional cascade reconstruction can be made for virtually all incident trajectories. The scintillator bars can be fully active bismuth germanate (BGO) crystals or plastic scintillators in a metal matrix that acts as the absorber, as shown in figure 2. The bars can be read out by inexpensive silicon PIN photodiodes. Both ends of the bars would be instrumented, and the location and direction of the particle-induced cascade would be ascertained both by determining which bars were involved and by calculating the impact point by examining the relative amplitudes of signals at each end of the bars.

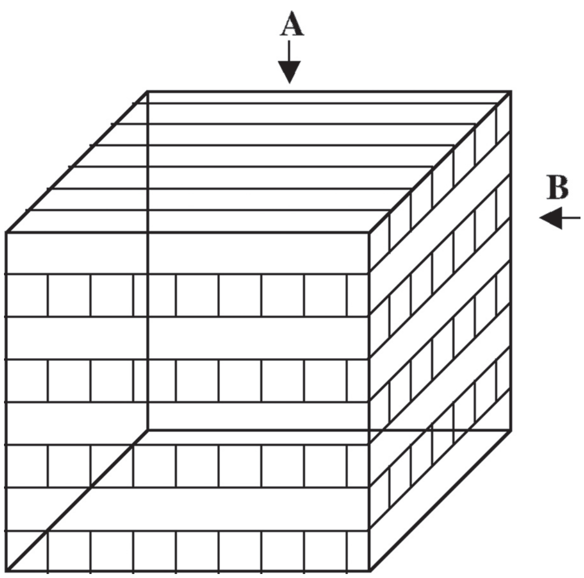


Figure 1. Schematic arrangement of cubic calorimeter showing successive layers of scintillator bars rotated 90°.

Also, using GEANT 3, we studied and optimized the design of the prototype detector, which will necessarily be simplified compared to the flight instrument. An important feature of the prototype design is that it can be reconfigured to simulate the detection by the flight instrument of particles coming from different directions. This is important in understanding the response of the detector, including its energy resolution and tracking angular resolution, as a function of the incident direction relative to the planes of detector bars. Preliminary Monte Carlo simulations of the prototype show that the needed performance requires about 400 channels of readout. A readout system, based on previous work in Code 661, has

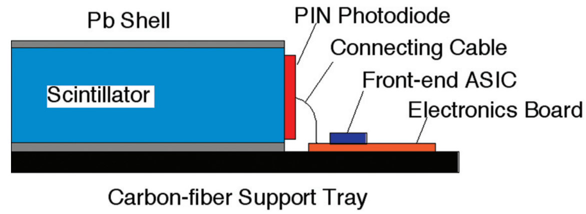


Figure 2. Schematic of scintillator bar showing a plastic scintillator sheathed in Pb with photodiode readout.

been studied using commercial 128-channel IDEAS TA1 ASICs. We have also carried out initial mechanical and optical designs of the prototype detector.

The primary intent of the instrument under study is to detect high-energy cosmic-ray protons and nuclei. We have extended its capability to study cosmic-ray electrons as well. The issues of energy resolution and particle identification involved in measuring both hadrons and electrons with the same instrument were carefully studied during FY 2003, and the results were presented by Alexander Moiseev at the XXVIII ICRC meeting in Tsukuba, Japan, in August 2003. The beam test prototype will be designed for the detection of both hadrons and electrons. The main problem in measuring high-energy electron spectra with such a simple instrument is to effectively separate electrons from the far more numerous protons. Preliminary simulations are very encouraging, and the approach will be examined in the beam test.

Planned Future Work:

In FY 2004 we will carry out additional high-statistics simulations of high-energy electron measurements. We will also complete the design and fabrication of a cubic calorimeter prototype. The beam test of this prototype is currently scheduled for September 2004 at the CERN SPS. We will expose the prototype to hadron (proton and pion) beams from incident directions spanning a range from normal to all layers (direction A in figure 1) to parallel to half the layers (direction B in figure 1). We will also test the ability of the calorimeter to identify incident electrons by exposing the prototype to high-energy electron beams at the SPS as well as by analyzing the proton data to determine what fraction of protons may be misidentified as electrons. We expect the cubic calorimeter to be capable of distinguishing electrons from protons at a sensitivity of better than one in ten thousand.

Summary:

The calorimeter we are developing will have about three times more collecting power in measuring cosmic rays compared to "traditional" calorimeters of the same mass. This improvement in efficiency could be used to increase the statistics obtained from a mission or to decrease the cost of the mission by reducing the time needed in space or on a balloon to collect significant amounts of data. For Goddard, this is an enabling capability for detecting high-energy cosmic rays, which are far less common than lower-energy cosmic rays from the Sun. Theese cosmic rays enter the detector and create a shower or cascade of secondary particles, the energy of which are measured by conventional partical detectors. In addition, our cubic calorimeter enables the measurement of high-energy electrons by providing powerful identification capabilities that separate electrons from the much more numerous protons. Electron cosmic rays create particle showers that are narrower and end more quickly than proton cosmic-ray-induced showers. We get two detectors for the price of one, so to speak. The criteria for success of the present program will be to show that the cubic calorimeter can provide the needed energy resolution (about 40%) and resolve the location of incident particles well enough (radius of error about 0.5 cm) to meet the requirements of a mission to make direct measurements of high-energy cosmic ray protons and nuclei.

Thin film stacks for enhanced X-ray reflection in the 1-4 keV range

Principal Investigator: Scott Owens (Code 551)

Co-Investigators: Peter Serlemitsos (662)

Initiation Year: FY 2003

FY 2003 Authorized Funding: $55,000

Actual or Expected Expenditure of FY 2003 Funding: $20,000 for USRA contract (Dr. Yang Soong) to fund installation and alignment of reflector foils in housings for performance measurements; $6,400 for contract to Mentor Technologies (Larry Olsen) to fund measurement of foil performance before and after enhancement coating; and approximately $3,000 for equipment and maintenance.

Status of Investigation at End of FY 2003: Procurement delays in FY 2003 forced us to delay this work into FY 2004. We will continue to work from the FY 2003 funding, which should be sufficient for this study.

Expected Completion Date: late 2004

Purpose of the Investigation:

We hope to improve the efficiency of reflecting celestial X rays onto detectors in space-based X-ray telescopes. Our investigation deals with "soft" or lower-energy X rays that can be reflected toward detectors by mirrors placed at shallow angles, analogous to rocks skimming across the surface of a lake. X- ray photons are far more energetic than visible light photons, and tend to behave much more like particles than like waves. Soft X-ray telescopes typically operate in the energy range of 0.1-10 kilo-electron volts (keV). The maximum angle of the X-ray mirror depends on the energy of the X rays of interest and the density of the reflecting surface. Gold is commonly used as the reflecting material for three main reasons: It is one of the denser materials available; it is inert; and it acts as a separation agent, making thin, replicated optics possibile. This third feature enables X-ray telescopes with cylindrical, concentric gold-coated mirrors of varying angles, a "Russian doll" arrangement, which maximizes collecting area. Gold, however, has a strong absorption edge at approximately 2.25 keV, which means it doesn't efficiently reflect X rays with energies between 2.25 and about 5 keV. Simulations indicate that using a stack of thin layers on top of the gold as the reflecting surface can mitigate the effect of the strong absorption edge, providing significant increases in efficiency over a simple gold reflector. Possible "films" include carbon, boron nitride, and aluminum oxide. We are investigating how to best put thin layers of low- and intermediate-density materials on the gold surface, either through direct replication or post-replication deposition.

Accomplishments to Date:

We have performed a variety of simulations to evaluate the performance of thin stacks for individual reflectors and for fully integrated scale mirrors for the Astro-E2 mission. The results indicate that at small grazing angles, the addition of a single, low-density layer is the optimum. This is because the critical angle of reflection is larger than the grazing angle, even for the lowest-density materials and highest-energy photons. For example, at a grazing angle of 0.5 degrees, a 60 Angstrom layer of carbon on top of the gold surface can enhance the reflectivity of a two-reflection system by as much as 30% at 2.5 keV, as shown in figure 1. In order to most clearly illustrate the benefit of this technology, we have simulated the on-axis effective area of an Astro-E scale mirror where the normal gold reflecting surface is compared to one with a uniform 60-Angstrom layer of carbon over the gold. For all regions but the very lowest energy, the addition of the carbon layer improves the on-axis effective area, as shown in figure 2.

Attempts to replicate low- and intermediate-density layers have been unsuccessful to date. We have studied the adhesion to glass of ion-beam-sputtered and magnetron-sputtered carbon, boron carbide, boron nitride, nickel and titanium. None of these materials provide the necessary separation to be used as the separation layer in replicated optics. Previous studies indicate that copper is a good separation layer, but the tendency of copper to oxidize makes it an unattractive material for this application. Our current thrust is to see if we can successfully deposit thin layers of low-density materials directly onto a previously replicated gold surface. The difficulty will be to keep the substrate temperature low so that the epoxy layer does not over-cure, while making the deposition process fast enough to be feasible.

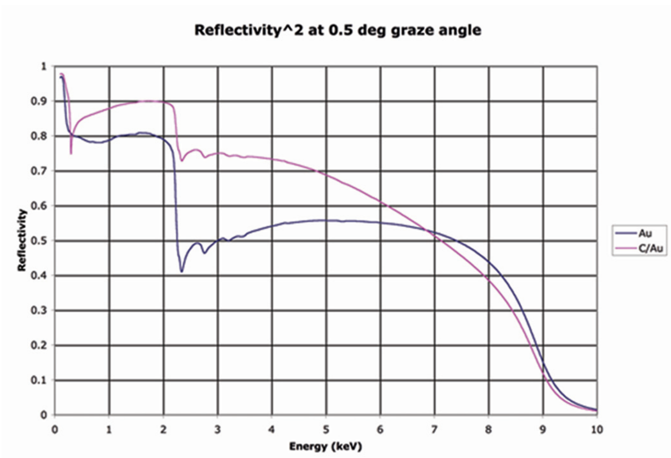


Figure 1 Comparison of the reflectivity squared for a thick gold layer, and a gold layer with 60 Angstroms of carbon on top.

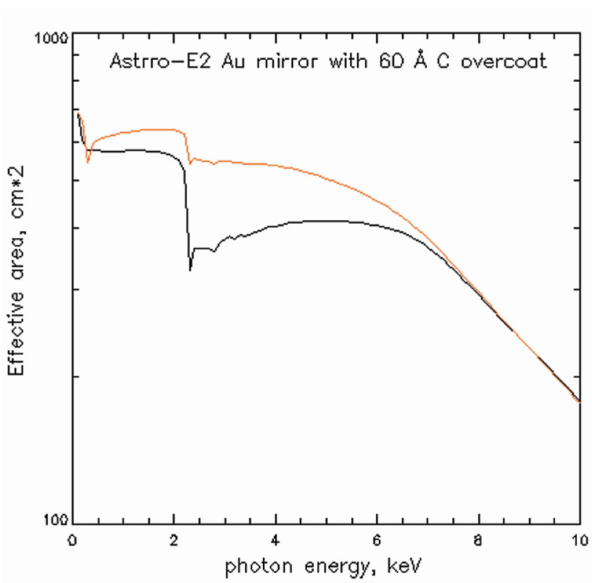


Figure 2 On-axis effective area of an ASTRO-E scale mirror. The black line is a normal gold reflecting surface. The orange line represents a 60-angstrom layer of carbon on top of the gold layer.

Fortunately, similar work has been done for the InFOCμS hard x-ray telescope, where Pt/C multilayers were deposited directly onto a platinum-replicated reflector. This research indicates that one can deposit carbon onto a reflector without damaging the surface roughness or the low order figure of the reflector.

Work is progressing on this front at this time. Four pairs of replicated gold reflectors are being mounted and measured for effective area and imaging quality. Once the initial measurements are done, these reflectors will have thin layers of carbon, boron carbide, boron nitride and aluminum oxide deposited on them respectively. They will be characterized for layer thickness and surface roughness, and then be reinserted in the alignment housings and measured for effective area and imaging quality again.

The primary difficulties associated with this research have not been technical, but financial. The midyear and Q4 purchasing blackouts have resulted in a six-month delay in purchasing deposition materials and funding the appropriate contractors in code 662 to support this work. A secondary difficulty involves the state of sputter-deposited materials, as compared to their “normal” chemical and mechanical properties. Boron nitride, for example, was our primary candidate for a direct replication substitute for the gold surface. It is used in industrial environments as a high-temperature lubricant and is relatively inert. Upon deposition, however, one of two things is happening: Either the sputtered BN is adhering to the glass substrate, or it is so lubricious that no material builds up on the surface. We follow the BN deposition with a thick layer of molybdenum, which normally adheres very well to glass, since we want to make sure that any separation properties are properly attributed to the BN layer and not a secondary layer. But, this layer combination adheres tightly to glass, indicating that the BN is either sticking to the glass or is not there at all.

Planned Future Work:

We intend to continue our post-replication deposition studies of carbon, boron carbide, boron nitride and aluminum oxide. Assuming that one or more of these materials can be successfully deposited, we will pursue a three-layer approach using the native gold surface, an intermediate-density layer, such as Cr_3C_2, and a low-density top layer. This type of design has greater benefit for reflectors at higher grazing angles than the simple two-layer design described earlier. Other possible approaches to improving the performance of soft X-ray telescopes using direct replication involve other dense materials such as platinum or iridium. Both of these alternatives are difficult to use on their own, since they both deposit under high compressive stress, causing deformation of the thin aluminum reflectors. However, these materials could be used if we can deposit thin layers, followed by thick backing layers of gold. Simulations indicate that 200 Angstroms of platinum or iridium are sufficient to yield “bulk” behavior, as long as that thin layer is followed by a thick layer of gold. Furthermore, brief studies from 1999 and 2000 indicate that these material combinations may be stable in the long term and provide a benefit commensurate with the additional design and production work necessary to implement in a flight mirror assembly. The results of these studies will be presented at the SPIE International Symposium on Astronomical Telescopes, June 21-25, 2004 in, Glasgow, Scotland.

Summary:

This is the first experimental study of using multiple-layer stacks to enhance the reflectivity of replicated soft X-ray optics. Most facilities that have been developed for production of replicated X-ray optics do not have the capability to deposit multiple layers without breaking vacuum. Our recent addition of a dual material deposition chamber for hard X-ray optics development makes this research possible. The largest and most immediate payoff for Goddard would be in relation to the Constellation-X Observatory. The current design for this mission is barely meeting the specified effective area requirement, and any additional mechanical constraints on the mirror assembly will result in an effective area less than the specification. This research may dramatically increase the performance of reflectors below 4 keV, allowing the optical design team to adjust the mirror parameters, and gain some amount of contingency area over the entire 1-10 keV energy band. Any enhancement in full mirror performance over 10% at 1.25 keV and/or in the 2.5 to 4 keV range will be considered a success. The inability of boron nitride layers to either separate or adhere at all in the first place has limited the “direct replication” portion of this research. As such, we have moved on to our secondary plan of post-replication deposition. This will be a more time-consuming process than any direct replication scheme, but we have been unsuccessful in identifying a low-density material that will act as a glass separation layer. We have also run into a variety of financial hurdles and delays due to the change over to the new IFMP system.

Miniature Stackable Mass Spectrometer Cavities of Permanent Magnet Films

Principal Investigator: Fred Herrero (Code 553)

Co-Investigators: Sachi Babu (553), Joe Grebowsky (695)

Initiation Year: FY 2003

FY 2003 Authorized Funding: $63,000

Actual or Expected Expenditure of FY 2003 Funding: In-house, $50,000; contracts with CUNY, $13,000

Status of Investigation at End of FY 2003: To be continued in FY 2004 with funds remaining from FY 2003.

Expected Completion Date: October 2004

Purpose of Investigation:

We are developing a stackable, magnetic-sector mass spectrometer that can sample molecules in a variety of settings, such as on the Lunar or Martian surfaces, in an astronaut cabin, or on Earth at volcanic sites or in situations of interest to homeland security, to name but a few applications. Current detectors, which use voltage or radio-frequency scanning to measure elements of different atomic weights, can be relatively bulky and can only measure one atomic weight at a time before switching to measure another atomic weight -- a very low duty cycle per atomic weight measured. Our device operates as a spectrograph; that is, it measures all the atomic weights in the range of interest, providing 100% duty cycle. Furthermore, it is stackable to reduce the mass and volume of the detector with little or no reduction in sensitivity and mass resolution. Our device also relies on magnetic fields, which is actually an older, time-tested technique. Essentially, a magnetic field of a known strength can deflect a molecule by a certain amount depending on its atomic weight. The special focusing properties of our magnetic spectrograph enable us to detect an entire range of masses at one time. Key to our instrument is a permanent magnet “film” magnetic sector. This is a thin film of a magnetic alloy, such as samarium-cobalt, deposited on a suitable substrate. Such films are capable of providing large magnetic fluxes in the range of 1,000 to 8,000 Gauss (a refrigerator magnet is 100 Gauss), sufficient to yield magnetic sector mass spectrometers and spectrographs with first-order focusing in one-centimeter linear dimension. Our investigation seeks a way to reduce the spectrometer volume to several milliliters.

Accomplishments to Date:

We have examined the properties of the D-magnetic sector developed at Goddard several years ago with DDF funds for ionospheric sounding rocket experiments. We selected the magnetic-D configuration because it offers an electrostatically adjustable mass range and first-order focusing operation with large radii at small deflection angles. The latter makes it possible to operate at magnetic fields much less than the maximum 8 kG (kiloGauss) expected from the permanent magnet films. The permanent magnet films are described in the current literature by F. Cadieu of CUNY, New York.

The main disadvantage of magnetic sectors is the bulky configuration associated with the volume and mass of the permanent magnet or electromagnet. Our thin film approach overcomes that disadvantage. Each magnetic sector consists of two permanent-magnet thin-film plates separated by a gap of about 1 mm, with rectangular dimensions on the order of 1cm x 1cm and thickness in the range of 0.01 cm. The magnetic field in the gap is perpendicular to the broad flat area of the plate as shown in figure 1, showing two plates mounted with north and south poles opposing, to provide a uniform magnetic field cavity in which the ions may move predictably subject to the uniform field between the plates.

This approach offers a dramatic reduction in size over the conventional magnetic sector mass spectrometers with bulk permanent magnets or electromagnets. However, the entrance aperture depends on the linear dimension of the spectrometer, and a miniature spectrometer of a single sector (one pair of plates) is necessarily less sensitive than a conventional size spectrometer. Nonetheless, because the magnetic sectors are thin enough to be stacked one above the other, a 10 to 20-fold increase in sensitivity is possible. Detection from the combined stacked sectors is done on a single micro-channel-plate detector with a one-dimensional position-sensitive detector anode properly aligned with the stack (figure 2).

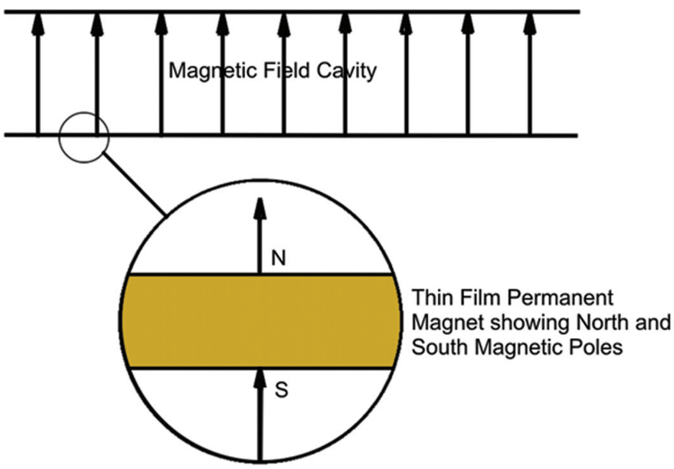


Figure 1. Magnetic field cavity produced by two permanent magnet films mounted on thin substrates. The insert shows that the magnetic films are magnetized in the same direction as required to make stackable cavities.

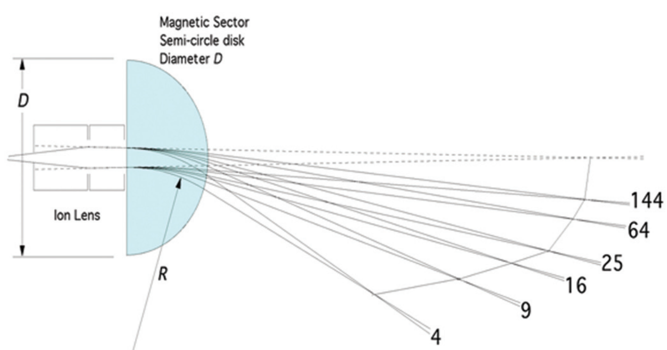


Figure 2. D-magnetic sector with diameter D. The trajectories incident on the ion lens from left are accelerated to energy E and focused at point Q on the far right where they would converge in the absence of the D-magnetic sector. The incident trajectories contain masses 4, 9, 16, 25, 64, and 144 amu, which are dispersed as shown by the magnetic field sector. The low mass range, 4 to 25 amu, is focused approximately along a straight line. A position sensitive detector placed along the line 4-9-16-25 will detect all the masses in this range simultaneously. The mass range can be adjusted with a change in the energy according to equation. 1.

Figure 2 shows the results of simulations for a magnetic-D region (semicircular disk) with diameter D and an ion lens on its left side. Ions incident from the left are accelerated to energy E and focused on distant point Q by the ion lens. In the simulation shown, the pre-focused ion beam enters the D-magnetic sector with a convergence of ±1° and covering a width about one-sixth the diameter D. Such a large beam was selected to illustrate the performance of the D-sector under conditions of large geometric aberrations. The resulting trajectories nonetheless show that there is a focal region that is approximately linear and flat in the mass range from 4 to 20 amu. Increasing the energy by a factor of 4 changes the mass range from 4-20 amu to a range of smaller masses by a factor of 4, to 1-5 amu. Similarly, decreasing the energy by a factor of 4, changes the mass range to a higher range of masses, 16-80 amu.

The ions with mass of 4 amu are shown following a trajectory with radius R inside the magnetic sector. The figure is drawn to scale, and the radius R shown for mass 4 amu is approximately equal to the diameter D of the D-sector. Trajectories for masses 9, 16, 25, 64, and 144 are also shown with the focal points correspondingly labeled. For kinetic energy E in eV, magnetic flux B in kiloGauss, and radius R in cm, the mass of the ion is given by:

$$m = 48.23 \frac{R^2 B^2}{E}$$

(equation 1)

With this relation, a magnetic field of 1 kG will focus ions of mass 4 amu in a radius R = 2 cm, at a kinetic energy of about 48.2 eV at position 4 in Figure 2. As the energy changes, so does the mass arriving at position 4; this is the key to adjust the mass range as discussed below.

Kinetic energy in the range from about 10 eV to about 500 eV are feasible for the operation of this device; the lower the energy, the larger the magnetic field required to operate with a given size magnetic sector. Figure 3 shows the mass as a function of the trajectory radius for 20 eV ions and three fluxes of magnetic field, 0.25, 1, and 4 kG. The smallest mass to be detected is 1 amu, that of atomic hydrogen. In our application, the trajectory radius should always be greater than about 2 cm. Figure 3 shows that the magnetic field flux should be significantly larger than 0.25 kG to obtain acceptable performance. At 1 kG, the radius goes comfortably from 2 to 10 cm while the mass increases from about 60 to 1000 amu. Increasing the energy to 200 eV would change the mass range to cover 6 to 100 amu.

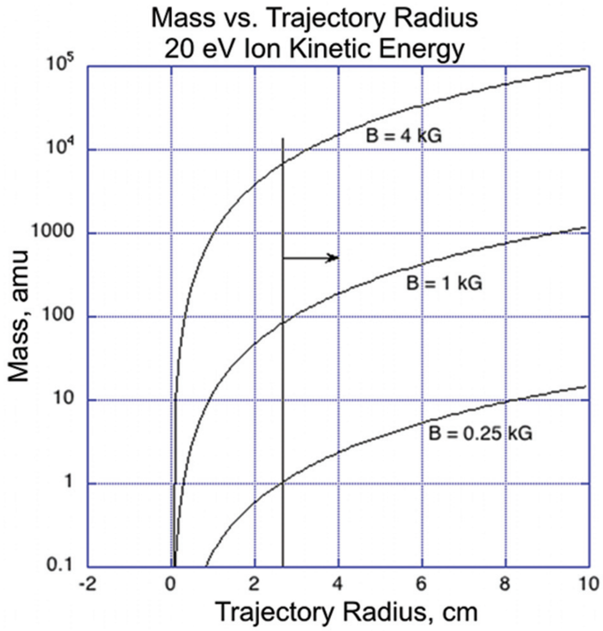


Figure 3. Variation of mass vs. radius of ion trajectory for fixed magnetic flux and io n kinetic energy of 20 eV. The figure shows that the magnetic field should be significantly larger than 0.25 kG to obtain acceptable performance at a reasonable energy. At 1 kG, the radius goes comfortably from 2 to 10 cm while the mass increases from about 60 to 1000 amu. Increasing the energy to 200 eV would change the mass range to cover 6 to 100 amu.

It is clear that miniaturization as we expect requires a flux in the range of 1 kG. In a report received January 28, 2004, from Prof. Cadieu, preliminary results show that 0.1 kG can be achieved without the aid of an external yoke in a configuration like the one shown in figure 1. Prof. Cadieu has also produced an external yoke of very low mass, about 80 grams to enhance the magnetic flux further. This result places the approach in figure 1 in jeopardy and requires further study to see if a factor of 3 enhancement is feasible to reach 0.3 kG in a 1-mm gap. Other approaches are suggested from the results presented in the report; the most obvious alternative uses a different configuration 1 kG in flux that may achieve focusing by virtue of the non-uniformity of the magnetic field. However, this alternative may make stacking difficult, though it would still provide drastic reduction in volume and magnetic moment in the spectrometer.

Mass spectrometers typically operate with single-point detectors at the focal plane, and detect one mass at a time by scanning energy. For example, a point detector could be placed at position 16, the point for mass 16 amu in figure 2, and mass could be scanned by scanning the energy. We call this mode of operation the "spectrometer mode". One disadvantage of the spectrometer mode of operation is signal loss due to the time taken up by the energy scan. Our D-magnetic sector may be used in "spectrograph mode" to detect all the masses in a given mass range simultaneously. In addition to enhancing sensitivity, this mode simplifies the operation because energy is kept fixed for the given mass range. For example, in figure 2, a position sensitive detector placed along the line 4-9-16-25 detects the mass range 4-25 amu with a 4 kG field and D-diameter if 1 cm at a kinetic energy of 192 eV. Setting the kinetic energy to 96 eV changes the mass range to 8-50 amu. Similarly, a D-diameter of 2 cm will give a mass range of 16-100 amu with kinetic energy set at 192 eV. We note that the important region of the D-magnetic sector is the small region where the ions move; volume may be minimized by removing those sections of the D-region above and below the area containing the ion trajectories, with due attention to fringing field effects.For very-high-resolution work, the mass range may be reduced to improve mass separation over a flat detector at all positions on the detector. For example, the detector may be restricted to a narrow range within positions 4 and 9 in figure 2 to provide mass range 20-28 amu with a 2 cm D-diameter/4 kG field/192 eV energy. If, as anticipated, focusing is optimum in this range, our 100-channel ASIC detector will provide a detectable change in mass Δm of about of 0.08 amu over this range. The average mass in this range being 24 amu, the mass resolution achieved would be $m/\Delta m = 300$. We note that $m/\Delta m = 50$ is required for most ionospheric applications in sounding rocket and satellites, but higher resolution will be required for homeland security applications, and may be required in other space science missions to Earth or the planets. Higher mass resolutions should be achievable in narrower mass ranges (e.g., 24-26 amu for $m/\Delta m = 1200$), or, if the quality of the ion optics allows it, higher mass resolutions with larger format detectors (e.g., 1000-channel detector).

In laboratory experiments, the gas to be analyzed is usually ionized in an ion source and the resulting ions are accelerated electrostatically and injected into the mass spectrometer. Thus, in laboratory applications all species incident on the spectrometer have the same kinetic energy, consistent with our simulations of figure 2. In contrast, in low-earth orbit, all particles enter the detector at the same velocity, about 8 km/s, and different masses will pass through the spectrometer with different kinetic energies. For atomic oxygen, the energy is about 5 eV and for molecular nitrogen about 9 eV. Since the magnetic sector deflects particles according to their momentum, mass separation will still occur, but the locations of the mass peaks will be somewhat different from those shown in figure 2, yet still distinguishable. We are currently studying the implications of this effect on mass resolution for those space science applications that may require mass resolutions higher than 50. Accelerating the ions will reduce this effect in proportion to the acceleration voltage. The ion source to test the above spectrometer is in place in Code 553, and the MCP detector and electronics are being assembled for tests in vacuum as soon as the first spectrometer is assembled.

Planned Future Work:

The above shows that the important design parameters for the D-magnetic sector are the D-diameter, the magnetic field intensity B and the feasible kinetic energy range. The above also shows that it will be possible to obtain satisfactory operation of the spectrometer with magnetic fields of 1 to 4 kG. Of course, if we obtain the magnetic field intensity of 8 kG, a factor of 4 more flexibility in the mass range is obtained.

Following award of purchase order to CUNY, design and selection of magnetic film characteristics will be done (This project submitted a purchase request to Prof Cadieu of CUNY in 2003). As soon as the permanent magnet films are received from CUNY (two to three months after receipt of order), the magnetic-D prototype will be assembled and tested with the circuits already prepared. We have begun design of an alternative fixture without the permanent magnet films. This uses bulk permanent magnets with the D-shape to test the ion-optical aberration properties of the magnetic-D with a view to optimizing aperture size selection. In addition, this work will prepare the test fixtures and electronics to make them all operational for the eventual arrival of the permanent magnet film spectrometer.

Summary:

This project offers a new design for the magnetic sector of mass spectrometers that (1) increases sensitivity by a factor of 10 to 20 by stacking sector units, (2) reduces the internal spectrometer volume to 5 to 10 milliliters to make it compatible with the smallest turbo-molecular or the most recent MEMS pumps under development, and (3) reduces the entrance aperture to $10^{-2}cm^2$, which translates into a device that may used under many different conditions in space science and ground-based application such as homeland security. The significant level of miniaturization to be achieved by this approach, coupled with our low-power ASIC (application-specific integrated circuit) amplifier and readout electronics, may make possible a "pocket" mass spectrometer operating on alkaline batteries. Such miniaturization will enable Goddard to maintain a leadership position in future constellation missions with 100 nanosats or more, and also in multiple applications in Lunar and Martian surface exploration and atmospheric composition measurements on Mars. The criteria for success include achievable useful resolution ($m/\Delta m$) of 50 or more; an aperture of about 10^{-2} cm^2; an internal volume of 10 cc in final product; and low outgassing of permanent magnet film structures to allow operation with small pumps of small gas handling capacity. Technical risk factors include saturation of magnetic flux, as already suggested in Prof. Cadieu's initial results; this point is far from settled and requires further study. Another risk issue involves outgassing of the permanent magnet film structures for compatibility with small pumps; this issue will be evaluated in our own ion beam facility with the first prototype received from Prof. Cadieu after he is funded. Finally, we must demonstrate acceptable resolution and sensitivity in a final product with low internal volume.

Flux Transformers for Magnetic Calorimeter X-ray Detector Arrays

Principal Investigator: Thomas Stevenson (Code 553)

Co-Investigators: Simon Bandler (662, UMD), F. Scott Porter (662), Enectali Figueroa-Feliciano (662), Caroline Stahle (662), Wen-Ting Hsieh (553), Travis Travers (553), Brett Bethke (NASA Academy), George Seidel (Brown University), Suzanne Romaine (Smithsonian Astrophysical Observatory)

Initiation Year: FY 2003

FY 2003 Authorized Funding: $50,000

Actual or Expected Expenditure of FY 2003 Funding: Code 553 contractor support, $25,000; photomasks, $5,200; silicon wafers, $2,600; Code 662 contractor support, $11,000; cryogens/machining, $6,000

Status of Investigation at End of FY 2003: To be continued in FY 2004 with additional DDF funding

Expected Completion Date: August 2004

Purpose of Investigation:

We are investigating a new type of instrument, a high-performance X-ray calorimeter, that can measure X rays emitted from near black holes and other celestial objects at a resolution required by future ambitious X-ray missions, such as Constellation-X, the Micro-Arcsecond X-ray Imaging Mission (MAXIM) and Generation-X. Such an instrument, measuring the heat deposited by a single X-ray photon, is one of the technological advances required for these missions. Goddard is actively developing two detector technologies to demonstrate the required energy resolution. These are two types of thermometers: an ion-implanted silicon thermistor, and superconducting Transition Edge Sensors (TES). Both measure temperature changes as a function of electrical resistance within the detector. An ion-implanted silicon thermistor will be used for the Astro-E2 mission; the TES is on the drawing board for the Constellation-X mission. We are investigating a third type of detector, a "magnetic" X-ray calorimeter that uses dilute paramagnetic atoms (such as erbium) in a metallic host (such as gold). Here, the degree of magnetism is a function of temperature change. At the universities of Brown and Heidelberg, researchers have shown that this method yields better energy resolution than the other two methods. However, testing has been performed with only a single pixel. We are investigating the method for use in a large array, for future missions will have thousands of pixels. More pixels mean more complexity. Specifically, we are examining whether a thin-film transformer can provide efficient coupling between a paramagnetic sensor and a Superconducting Quantum Interference Device (SQUID) amplifier fabricated on separate chips -- an early step in the long-term goal of enabling the type of resolution needed to detect matter falling into a black hole.

Accomplishments to Date:

The approach we took was to use a superconducting planar transformer with slotted washer as a flux guide. The flux guide gives strong and equal magnetic coupling between any one of the many transformer coil windings and a magnetic sample near or overlapping the washer edge. When counter-flowing currents under each winding of the transformer coil encounter the slit in the washer, they return mostly around the washer's inner edge. Thus the slotted washer effectively translates the current from any transformer winding location to a current concentrated on the washer edge next to the sample, as illustrated in figure 1.

We carried out detailed numerical modeling to optimize the design and predict achievable coupling strength. For a

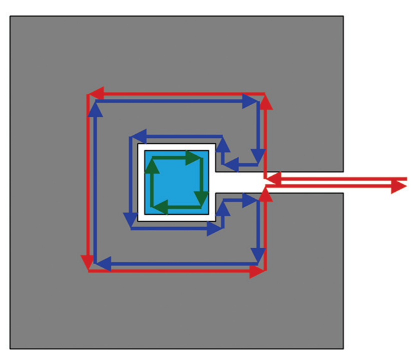
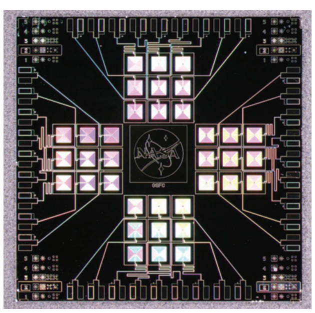


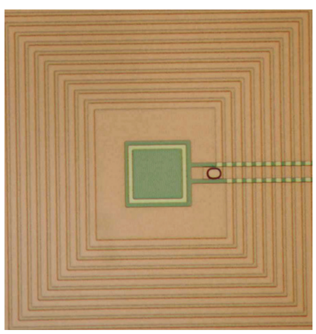
Figure 1. Sketch of current flowing in one turn of the transformer coil (red), counter-flowing current in slotted washer (blue), and effective current in sample (green).

fixed sensor diameter and coil pitch, we calculated the optimum washer width for various assumed interconnect inductances. We solved for supercurrent distributions near the washer edge and calculated coupling strength at various positions within a 3-D sensor. We concluded that a compact transformer can be realized with coupling equivalent to only 2.7 times worse linear SQUID flux noise compared to placing the sample directly on the SQUID. (Instead of two times worse for an ideal transformer.)

We designed and procured photomasks, then fabricated arrays of flux transformers using optical lithography and reactive ion etching in the Goddard's Detector Development Laboratory. Each chip (figure 2a) has four 3x3 arrays of transformers. In the center of some transformers, we included a niobium ring (figure 2b) that will screen down the self-inductance of the transformer coil to various degrees depending on the magnetic coupling strength at the ring location. In that way, we will be able to verify our modeling without the expense of depositing erbium-doped gold paramagnetic sensor layers during this DDF project. A microstrip configuration gives very low inductance on-chip connections from coils to bonding pads (figure 2c).



(a)



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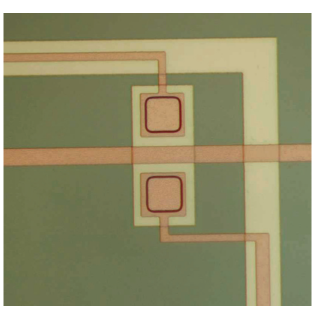
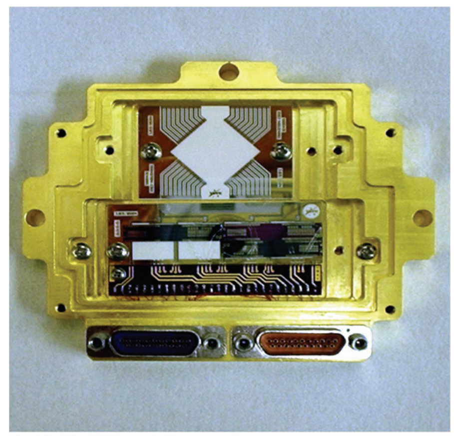


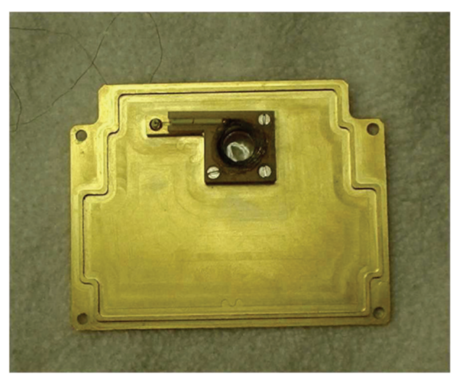
(c)

Figure 2. (a) Completed 12-mm square chip with four 3x3 transformer arrays. (b) View of center of transformer coil with niobium sample ring inside. Pitch of windings in niobium coil is 6 μm. (c) Microstrip connections and superconducting vias for crossovers.

In parallel with the fabrication work, we designed, built, and wired a testing platform in an adiabatic demagnetization refrigerator, acquiring all the necessary SQUIDs and interconnection hardware. We were able to obtain SQUIDs with a suitably large input coil that is compatible with the SQUID electronics used with our TES detectors for the Constellation-X project. We adapted our TES testing box design to make a new mounting box for this work (figure 3). With summer student help, we made and installed a field coil in the box lid capable of producing dc magnetic fields for biasing magnetic calorimeters.



(a)



(b)

Figure 3. (a) Detector box developed for flux transformer measurements. (b) The underside of box's lid showing the field coil.

We characterized the SQUIDs in the detector box, and measured the stray input inductance and shunt resistance of the input circuit by measuring the spectrum of Johnson noise at various subkelvin temperatures. By measuring total inductance under different conditions, we will be able to characterize the flux transformer. We have completed baseline measurements with a wirebond shorting our interconnecting leads together in place of the transformer chip. From this data, we measured the stray inductance of our interconnecting leads.

The work we have accomplished so far was used in supporting a proposal submitted in October 2003 to the Code R Mission and Science Measurement Technology NRA by Goddard, NIST, Brown University, and the Smithsonian Astrophysical Observatory.

Planned Future Work:

We now have devices available to test, and an extension proposal requesting more time to measure and analyze the performance of our flux transformers has been approved for FY 2004. An IRAD proposal to expand the scope of magnetic calorimeter development at GSFC has also been selected for funding in FY 2004. Furthermore, if selected, our joint Code R proposal with NIST, Brown, and SAO would allow Goddard to build upon the work of this DDF, and an FY 2003 DDF on mushroom absorbers for magnetic calorimeters, in the development of magnetic calorimeter array technology for NASA missions.

Summary:

This work will experimentally demonstrate feasibility of using a multi-turn planar transformer with flux guide to efficiently couple a small magnetic calorimeter to an off-chip SQUID amplifier in the presence of stray inductance from interconnections. This, in essence, will enable the measurement of minute temperature changes in a detector from a single photon of light, from which one deduces the photon energy which provides insight into the process that emitted it. This innovation will be an enabling technology for the development of large-format arrays of X-ray detectors based upon magnetic calorimeters, and would help make this detector technology available to Goddard for use in the Constellation-X, MAXIM and Gen-X missions. The criterion for success is demonstration of the feasibility of efficient transformer coupling to arrays of detectors. The risks have been unforeseen fabrication difficulties and discrepancies between measured and predicted coupling. In fact, more sophisticated modeling than had been anticipated was found necessary for confidence in our design, and we also experienced difficulty reproducing a dry etch process for niobium that we had developed previously. As a result, the design and fabrication steps took extra time, and an extension into FY 2004 is required to complete measurements of magnetic coupling efficiency for the devices fabricated in FY 2003.

Fluorescent Probes for the Identification of Extra-Terrestrial Amino Acids

Principal Investigator: Harry Shaw (Code 562), Paul Mahaffy (915)

Co-Investigators: Shavesha Anderson (562), Jeannette Benavides (562)

Initiation Year: 2003

FY 2003 Authorized Funding: $50,000

Actual or Expected Expenditure of FY 2003 Funding: In-house expenses, $50,000

Status of Investigation at End of FY 2003: To be continued in FY 2004; transitioning to award from Astrobiology Science and Technology Instrument Development NRA 02-OSS-01

Expected Completion Date: December 2004

Purpose of Investigation:

One of the key goals of astrobiology is the identification beyond the planet Earth of the building blocks of life, such as amino acids. Fluorescence spectroscopy has the potential for great sensitivity in such identification. Fluorescence can occur when light passes through a chain of chemicals, gets absorbed, excites electrons in the chemical molecules, and then gets reemitted at characteristic wavelengths determined by the absorbing chemicals. Zeptomole-level (10^{-21} mole, or about 1,000 molecules) sensitivity has been reported when using chemiluminescent tags, which refers to the emission of light without heat, as is the case in bioluminescence. The Jet Propulsion Laboratory has developed a fluorescence instrument for planetary missions that provides a test for the presence of amine groups ($-NH_2$) using fluorescamine. Fluorescamine is initially non-fluorescent and becomes fluorescent in the presence of amine groups. All amino acids contain amine groups; if no other amine sources are present, it is a positive result for the presence of an amino acid. Our investigation plans a more aggressive use of fluorescence spectroscopic techniques to provide a sophisticated suite of chemistries capable of identifying a wide range of compounds, starting with amino acids.

Accomplishments to Date:

Our long-term objective is to develop specific chemistries, or means of identification, for each protein amino acid and several non-protein amino acids that are present in meteorites or that are expected to be produced in solar system ices by radiation processes. These chemistries will be designed to provide a substantial fluorescent output (either fluorescence, quenching, or polarization) in the presence of a single amino acid. If that objective proves untenable, the backup goal would be to produce seven or eight chemistries that would identify the amino acid by class. The idea is to embed the necessary chemistry constituents in a substrate, microwells (figure 1) or membrane. (For simplicity, call it a substrate.) The sample to be analyzed would be brought into intimate contact with the substrate. One would simply need to read the plate (with a spectrometer or camera) and record the results.

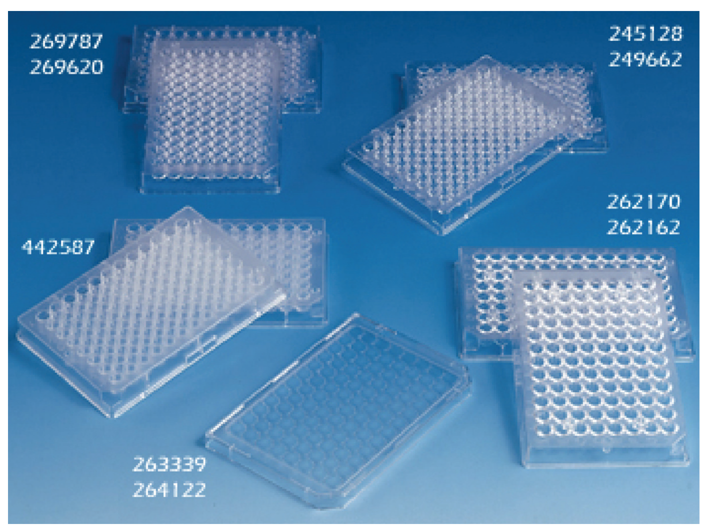


Figure 1. Commercial microwell plates.

We aim to: obtain some Mars analog rock samples, such as the Mars regolith simulant JSC Mars-1 (a mixture of anorthite, olivine, pyroxene, nano-phase Fe-oxides, and glass, feldspar, and Ti-magnetite), and characterize for background fluorescence; perform a literature search/R&D to develop suitable chemistries; develop a plan for making a multiwell substrate; and demonstrate the specificity of the reactions in vitro with loaded rock samples. (A regolith is a mass of weathered material, such as a rock fragment, resting on solid rock.) For a one-year DDF, we set a goal of identifying two specific amino acids or amino acid classes. For the larger astrobiology goals, we will perform a much broader set of amino acid identification.

We have obtained α-amino acids with various functional side groups, obtained samples of JSC-1 Mars Regolith, and purchased solvents and fluorescent probe dyes. We have performed excitation and emission fluorescence spectroscopy on the Mars Regolith and confirmed it to be essentially non-fluorescent. We have taken baseline absorption and fluorescence emission spectra on the as received amino acids. Spectra were taken over the UV-visible range (200nm-800nm). We found some unexpected fluorescence peaks that may be due to contamination in the as-received state. These amino acids come from a variety of sources, including direct chemical synthesis, extraction from vegetables, and fermentation from sugars. We have obtained titration curves on the as received amino acids and taken a few fluorescence spectra (e.g. Argenine) at 3 pH levels and examined different spectra.

The Mars Regolith has a smaller fluorescence than any of the analytes of interest and is highly insoluble in water and other common solvents. Both of these conditions are conducive to developing the analytical technique. We can, in essence, extract soluble compounds with little concern about background regolith fluorescence. Figure 2 show the emission and excitation spectra of the JSC-1 regolith. The as-received amino acids titrate out close to expected titration curves, however the fluorescence spectra may indicate a potential low-level contamination. No data has emerged that would indicate that the science approach would not work.

Planned Future Work:

We will obtain and purify bulk quantities of amino acids and finish baselining amino acid fluorescence with respect to pH using chromatographic techniques. We will perform radiation testing on potential fluorophores at the Michigan State University National Superconducting Cyclotron Laboratory. We will start fluorescence trials with the amino acids at selected pHs with both known pH-sensitive dyes and known functional-group-sensitive dyes, and we will purchase additional fluorescence agents to increase sensitivity of the techniques.

We will also develop the multiwell substrate concept and test out the UV-visible fluorescence on additional simulants.

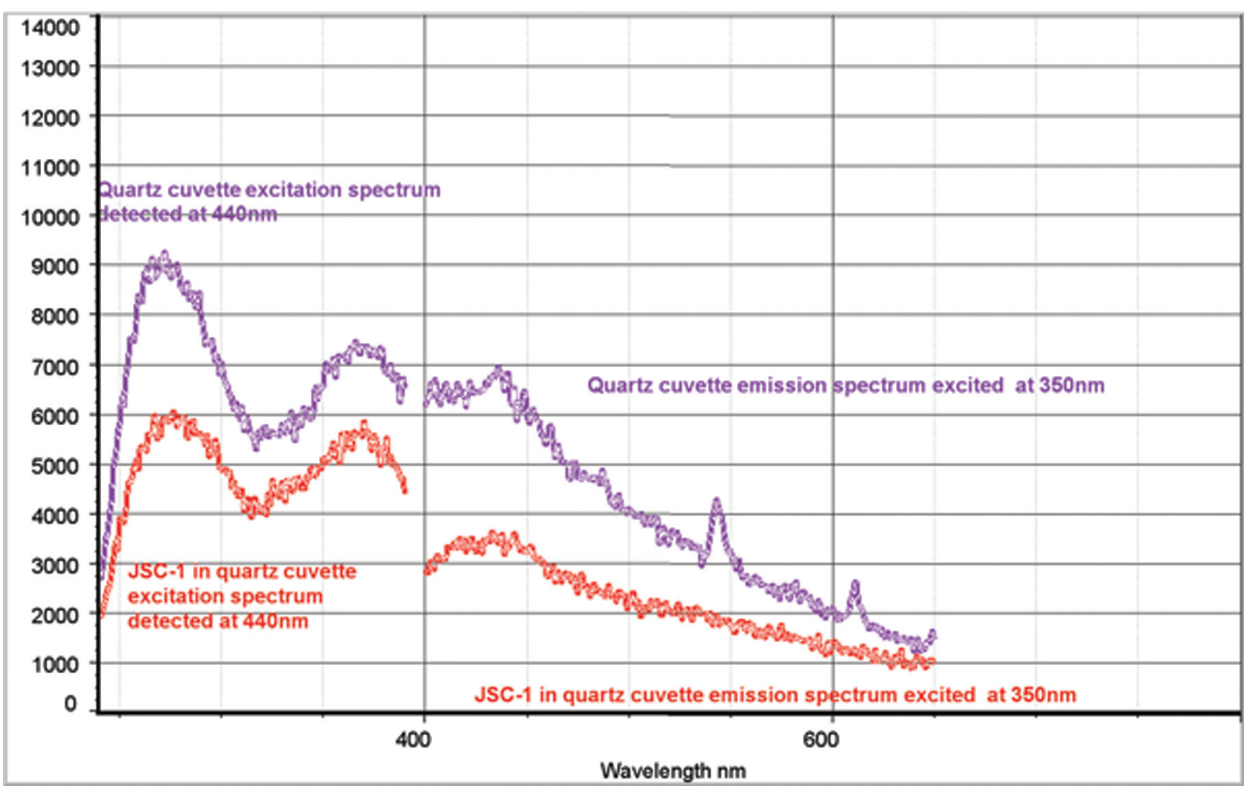


Figure 2. JSC-1 Regolith fluorescence excitation and emission spectra

We currently have: HWMK101 (Palagonitic Tephra, should expect water release around 100-200 and then fairly gradual decrease with temperature); HWMK979 (Jarositic Tephra, should have a very distinct H_2O and SO_2 release; also water release from palagonitic glass); HWMK775 (Phyllosilicate-rich Tephra, two phyllosilicates present, smectite and kaolinite, which give distinct H_2O releases; this is a very "wet" sample); JSC Mars-1 Simulant (Martian Bight Region Simulant, water release around 100-200 and then very gradual release with temperature); and Dolomite (Dolomitic Limestone, salts have been removed; should see two distinct CO_2 releases). We will develop plans to demonstrate specific amino acid detection in the presence of Mars regolith simulant and the sensitivity limits (how many nanomoles or femtomoles) present, and we will begin examinations on amino acids found in Murchison meteorite such as a-amino-n-butyric acid. Finally, we will transition the activity from a small DDF startup to a full investigation for an astrobiology fluorescence instrument.

Summary:

Fluorescence spectroscopy is a rapidly growing field in clinical biochemistry and medicine. There is the potential for a large, well-developed toolset that can be adapted for extraterrestrial use to find building blocks of life. The key is to first come up with simple reactions that can develop recognizable fluorescence characteristics in the laboratory specific to individual amino acids or classes of amino acids. Then one needs to integrate this knowledge into planetary instruments. Our project offers a new approach to detect extraterrestrial organic compounds: that is, pH-dependent fluorophores for identification of amino acids, coupled with commercial clinical chemistry technologies. Goddard can benefit from this approach to extend the usefulness of high-value planetary instruments that analyze extraterrestrial soils, dust particles and gases. A potential may exist to gather chirality information (left or right handedness) about organic constituents such as amino acids. Chirality plays a major role in the chemistry of living things on Earth. Our criterion for success is to obtain accurate, unique, repeatable fluorescence spectra for identifying amino acids, either individually or by class. Technical risk factors include the fact that (1) the intrinsic fluorescence of most amino acids is low but detectable, and deriving and amplifying fluorescence within the context of simple reactions that could be used on a spacecraft instrument is a large hurdle; (2) the purity of the amino acids used to validate the techniques must be very high, and current stocks will require additional purification via chromatographic techniques; and (3) radiation tolerance of the fluorophores has to be demonstrated.

Development of "Mushroom" Absorbers for Magnetic Calorimeter X-ray Detector Arrays

Principal Investigator: F. Scott Porter (Code 662)

Co-Investigators: Simon Bandler, Regis Brekosky, Caroline Kilbourne, Richard Kelley, Enectali Figueroa-Feliciano (662), George Seidel (Brown University), Suzanne Romaine (Smithsonian Astrophysical Observatory)

Initiation Year: 2003

FY 2003 Authorized Funding: $50,000

Actual or Expected Expenditure of FY 2003 Funding: Swales Aerospace, $20,000; University of Maryland, $10,000; supplies (mask sets, wafers, cryogens), $10,000; Toper, $10,000

Status of Investigation at End of FY 2003: pending transition to IR&D plus Code R MSMT

Expected Completion Date: August 2004

Purpose of Investigation:

The purpose of this investigation is to develop techniques for constructing overhanging "mushroom" absorbers on sensors with geometry that is unique to the requirements of magnetic micro-calorimeters. The magnetic micro-calorimeter represents a next-generation detector capable of providing the required energy resolution specified for future, proposed X-ray telescopes, such as Constellation-X, the Micro-Arcsecond X-ray Imaging Mission (MAXIM) and Generation-X. The micro-calorimeter measures the minute heat deposited by a single photon, or particle of light. Since having the absorber in contact with a supporting substrate will likely lead to a deterioration in detector performance, it is highly desirable to produce an absorber that overhangs the sensor, or "stem," in a geometry that is similar to the shape of a mushroom, where the absorber is located in the region of the mushroom "cap". (The procedure for building mushroom absorbers on top of magnetic sensors is described in figure 1.)

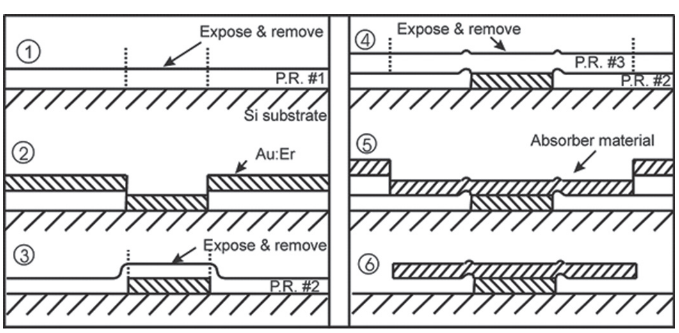


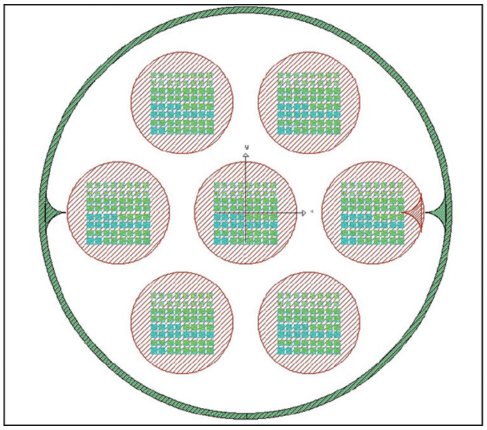
Fig. 1. Procedure for building mushroom absorber

Accomplishments to Date:

Once we achieve this construction, we then must test the arrays at cryogenic temperatures, a few degrees above absolute zero, to investigate mechanical and physical properties of the mushroom geometry for a variety of different disc and absorber dimensions. The final purpose of this work is to develop a new collaboration with groups developing this emerging technology.

We designed and procured mask sets carrying out this investigation. In figure 2a we show the design whereby a four-inch diameter wafer is divided into seven different regions. This is done because the precious metals deposition system uses one-inch-diameter sputter targets; so only one of the regions can be uniformly covered with thick gold sensor material during one deposition. Figure 2b shows an expanded view of one of the seven regions. The mask shows 64 square regions of typically 6x6 arrays. The gold sensor stems have diameters ranging from 20 to 150 microns. The gaps between the absorbers range from 6 to 12 microns, as well as a few arrays with more widely spaced pixels.

We built a new platform for testing these mushroom absorbers at low temperatures that could also be used for testing the flux transformers as part of a second ddf investigation. We acquired suitable SQUIDs for eventually testing the low temperature thermalization properties of these absorbers. It is the same platform as we are using to test high-efficiency flux transformers for another DDF project. The fully assembled and successfully tested set-up is shown in figure 3. The wires feed into the lowest part of the box through micro-miniature connectors. The SQUIDs are located in the lower



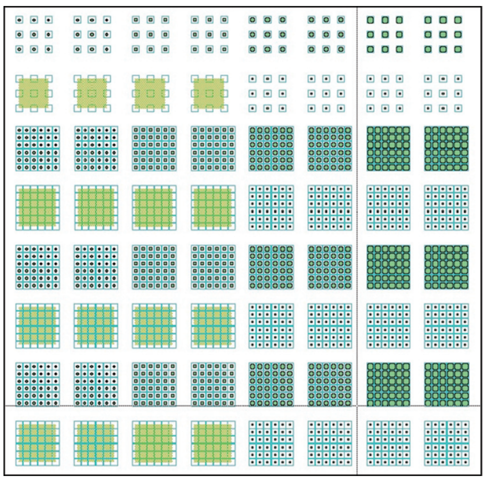


Figure 2. (a) Design of the first mask set. There are seven separate regions over which one-inch-diameter depositions can be made. (b) Overlaid masks showing different array geometries being tested. The small 6x6 squares depict the bismuth/copper absorbers positions, and inside the squares are the circular stems of various diameters.

half of figure 3 just above the connectors. In the top half of the figure, one can see a chip carrier on which we will attach our test devices. Suzanne Romaine at SAO, working with George Seidel at Brown University, was able to construct 10-micron-thick "stems" of our design in large arrays using our mask set. This involved developing processing capabilities to allow processing of the 4-inch-sized wafers that we need for subsequent processing at Goddard. She was successful in producing arrays of discs/stems.

During the year, Goddard was instrumental in forming a collaboration with other groups working on this emerging technology. Since our original DDF proposal, the Constellation-X technology development schedule has been extended, and thus there is now a period of opportunity over which magnetic calorimeters might be considered for this mission,

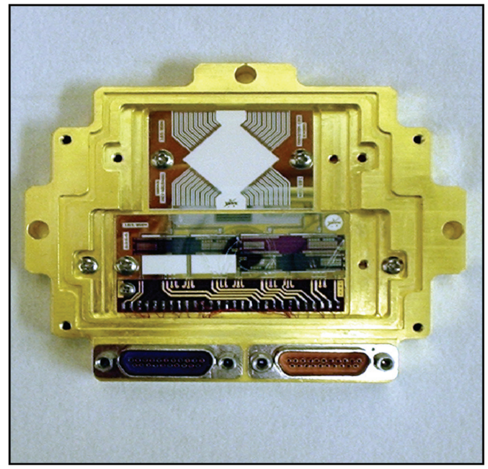


Figure 3. The set-up for testing mushroom absorbers.

as well as other future missions such as MAXIM and Generation-X. Our DDF work has allowed us to lead a new collaboration with all other U.S. institutions working on this technology to develop the technology required for serious consideration by Constellation-X. The other institutions are NIST, Brown, Heidelberg, Jena, Berlin and SAO. The U.S. institutions in this collaboration have applied together for NASA support in a Code R MSMT proposal entitled "Development of Magnetic Microcalorimeter Arrays for X-ray Astronomy". We hold monthly telecons to share progress. We are also considering working collectively towards proposing to build a focal plane array for RAM, the "Reconnection and Microscale" solar terrestrial probe. RAM will be supporting technology development starting in 2004, and our collaborative research effort will allow us to submit a very competitive proposal.

We have started to develop the techniques that are necessary for fabricating the absorbers on top of the stems to complete the mushrooms. We have been working hard to develop the most suitable recipe for processing the photoresists. This processing turned out to be significantly different to the processing that is required producing "mushroom" absorbers on transition edge sensor detectors. After several attempts we recently were successful in forming the necessary thick photoresist patterning. We had expected to yield our first devices by now, however the first wafer to be ready for the absorber deposition was accidentally broken. The next wafers are currently being made and we look forward to yielding our first "mushroom" devices soon. We have submitted an abstract to the SPIE Conference on "High Energy Detectors for Astronomy" to be held in Glasgow in June 2004 entitled "Development of Magnetic Microcalorimeters for X-Ray Astronomy".

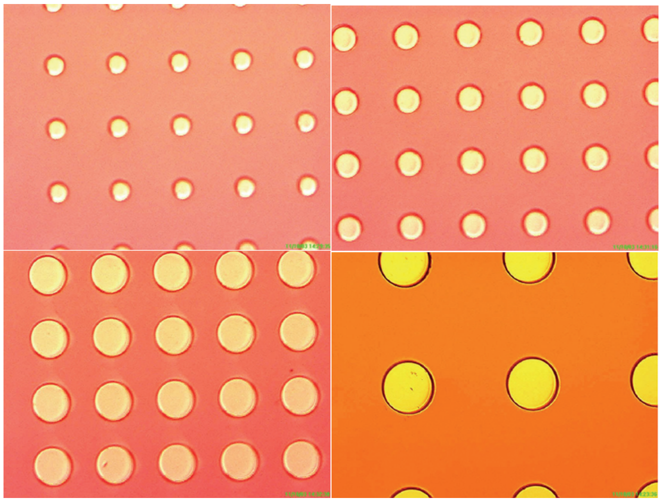


Figure 4. This figure shows arrays where the pitch is 250 microns and the stem size diameter is (a) 50 microns, (b) 100 microns, (c) 150 microns and (d) a closer view of 100-micron discs.

Planned Future Work:

We will continue to develop the fabrication techniques that will allow us to successfully construct large arrays of magnetic microcalorimeters with “mushroom” absorbers. We aim to integrate these construction techniques with the flux transformers developed under a separate DDF to allow us to test the performance of these microcalorimeter arrays. Over the last year there has been tremendous progress in magnetic microcalorimeter development. As we predicted in our original proposal, magnetic calorimeters have surpassed all other microcalorimeter technologies by demonstrating the best energy resolution so far achieved by a microcalorimeter of 3.4 eV (FWHM) for energies up 6.4 keV. This result was obtained by our new collaborators in Heidelberg.

This result was warmly received in a presentation at recent Constellation-X facility science team meetings. Further improvements continue to be made; and 2.5 eV may be achieved in the very near future, and less than 1 eV may ultimately be possible for detectors that do not require very high counting rates. We plan to build large-format array that will fulfill this potential.

Summary:

In this project we are now very close to being able to construct large-format array structures, which is key to being able to build large-format arrays of magnetic microcalorimeters. If this and other developments on magnetic calorimeters continue to be successful, there is excellent potential that this technology could be chosen for the focal plane array of Constellation-X and other missions. This would involve NASA/Goddard fabricating the arrays. Our criterion for success is the ability to construct rugged, uniform arrays of structures in the geometry necessary for freestanding “mushroom” – shaped magnetic microcalorimeter arrays. So far all technical obstacles encountered have been overcome. The risk remains that the proposed geometry will not allow us to build the arrays desired for it may lack the structural intregrity to function properly. We are now constructing these arrays.

High-Precision Mirror Reflectance Uniformity

Principal Investigator: Charles W. Bowers (Code 681)

Co-Investigators: Ritva Keski-Kuha (551), Bruce Woodgate (681)

Initiation Year: 2003

FY 2003 Authorized Funding: $60,000

Actual or Expected Expenditure of FY 2003 Funding: STET In-house, $8,000; Sigma Space Corporation contract, $40,000

Status of Investigation at End of FY 2003: To be continued in FY 2004 with funds remaining from FY 2003.

Expected Completion Date: April 2004

Purpose of Investigation:

The purpose of our investigation is twofold: to determine the level of mirror reflectance uniformity required for coronagraphy of extra-solar planets, and to make the first measurements of the current state-of-the-art reflectance uniformity for some candidate mirror coatings at the unprecedented high level of precision necessary for extra-solar planetary coronagraphy. Coronagraphy is a technique of blocking out a light source -- in this case, a distant star -- so that one can study dimmer objects such as planets orbiting near that central source. Reflectance is the fraction of light reflected from a surface of a mirror. We are also attempting to determine a method to correct errors of amplitude (square root of reflectance) and errors of phase (differences in path length) for an instrument already in orbit. It is expected that very small errors in reflectance uniformity (a few parts in 10,000) would lead to stray light levels, called "speckle," that would essentially render extra-solar, terrestrial-like planets invisible. Modeling is needed to quantify this. The large, primary mirror envisioned for the various proposed space coronagraphy missions is the likely source of most reflectivity non-uniformities. This is due, for example, to coating non-uniformities. However, no information exists at this extremely high-precision level, as well as at the spatial frequency distribution of non-uniformities, for the large optical components that are used for space telescopes. Such information is directly relevant to the success of future missions such as the Terrestrial Planet Finder (TPF) program, as well as several Discovery mission proposals.

Accomplishments to Date:

Substantial progress has been made toward completing all goals of the investigation. Figure 1 shows the calculated effect of wavefront amplitude non-uniformities on the performance of a candidate, Lyot coronagraph. For contrast at the level of extra-solar, Jupiter-like planets (contrast approximately $\leq 10^{-9}$) amplitude uniformity must be 0.18% or better. For extra-terrestrial planetary imagery (contrast approximately $\leq 10^{-10}$), amplitude uniformity must be about 2×10^{-4} (equivalent to single mirror reflectance uniformity of 4×10^{-4}) or less.

Calculations of ideal coating reflectivity non-uniformities due to the variation of the incident angle of light on an $f/2$ primary mirror are shown in figure 2 for gold and overcoated aluminum. Under these ideal conditions, we see that gold may just be a viable coating material. Simple, protected aluminum, however, may not be usable without a means of amplitude correction. Such a method was suggested in our paper, "A Novel Method of High Accuracy, Phase and Amplitude Correction for Coronagraphy" presented at the 2003 TPF Technology Expo, and also included the results of our simulations. An IR&D award was made to construct and test a laboratory version of the dual Michelson corrector proposed.

As proposed, we have constructed an instrument to allow measurements of coating uniformity to very high precision using witness samples from some typical coatings proposed for high-contrast coronagraphy. Figure 3 schematically illustrates our instrument design that is currently under test.

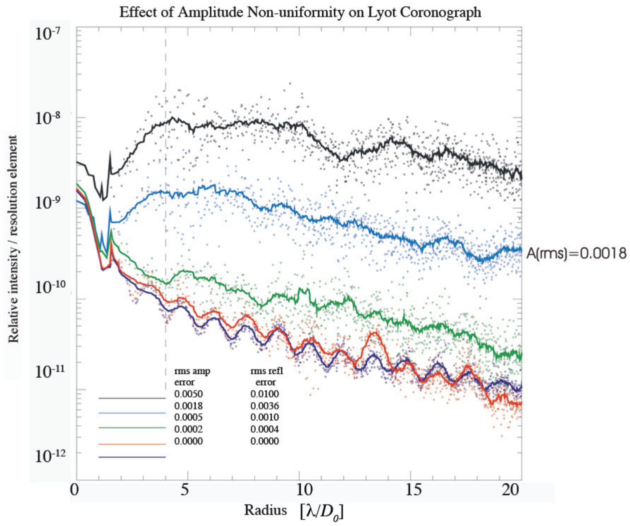


Figure 1: Simulation results of various rms levels of amplitude non-uniformities (indicated by labels to right of each curve for A(rms)≠0) on the contrast achievable with a Lyot coronagraph. Zero phase error is assumed for each simulation. The amplitudes follow a f^{-2} power law distribution with the indicated rms level errors. The Lyot coronagraph has a focal plane Gaussian profile transmission stop with half maximum transmission at 4λ/D and a hard, Lyot stop of radius 0.72. Contrast levels of about 10-9 can be achieved with an amplitude rms of about 0.0018 (single mirror reflectivity of about 0.0036); at an rms non-uniformity of about <0.0002 amplitude (single mirror reflectivity of about 0.0004) there is no essential difference from perfect uniformity.

We produce relative reflectance measurements between a set of witness samples (held in the sample mirror holder) and a fixed reference mirror at a polarization angle set by the in-line polarizer. The reference and sample beams are chopped to reduce sensitivity to source amplitude and detector sensitivity drift. An integrating sphere has been added to reduce sensitivity to non-uniform detector response. The detector signal is digitized, sampled and averaged to reduce random measurement fluctuations.

To achieve relative reflectance precision of $1x10^{-4}$, both random noise and systematic errors must be reduced to very low levels. The result of a three-minute measurement of a test sample is illustrated in figure 4 showing the deviation from the mean of the reference-to-test relative reflectance. The random system noise has been reduced to very low levels; over this time period the variation in relative reflectance is only $4x10^{-5}$, about 2.5 times below our goal of $1x10^{-4}$. This level of random noise is now typical of what we are achieving and is very satisfactory. Figures 5 and 6 show relative reflectance measurement stability over long periods.

Our efforts are currently focused on reducing all systematic errors in the instrument to allow us to achieve repeatable, relative reflectivity at the 10^{-4} level. The results of one data run obtained overnight are illustrated in figure 6. The relative reflectance level deviations about ±5x10-3 from average, about 50 times our goal.

Also shown is the monitored temperature level over the same time period; the correlation between reflectance and temperature drift is obvious. After making some improvements in the system, we have obtained results with relative reflectance drift reduced to about $\pm 1x10^{-3}$, about a five-times improvement. (Only a short period of temperature monitoring was available during this run due to equipment problems, but it showed a change of several degrees in a two-hour period. The periodic error in these measurements is also correlated with room temperature changes.) Our precision is presently about ten times lower than our goal, however it is still significantly greater than typical reflectance measurements (about 1%). We are at the point where we should begin to measure

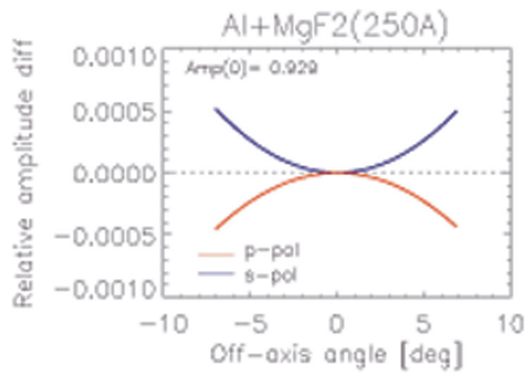


Figure 2: Calculations of the non-uniformity of wavefront amplitude for an $f/2$ primary mirror for coatings of bare gold and an overcoated aluminum mirror.

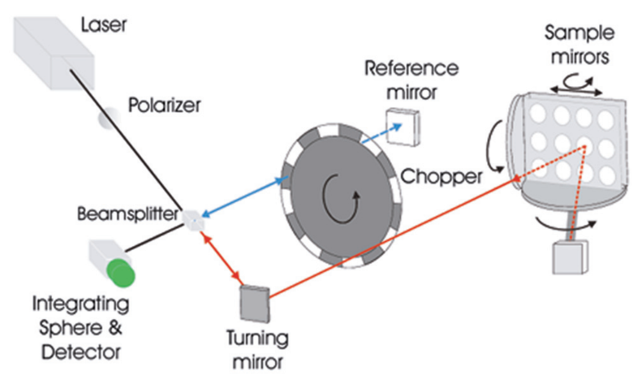


Figure 3: A schematic layout of the principle hardware components of our reflectance measurement system.

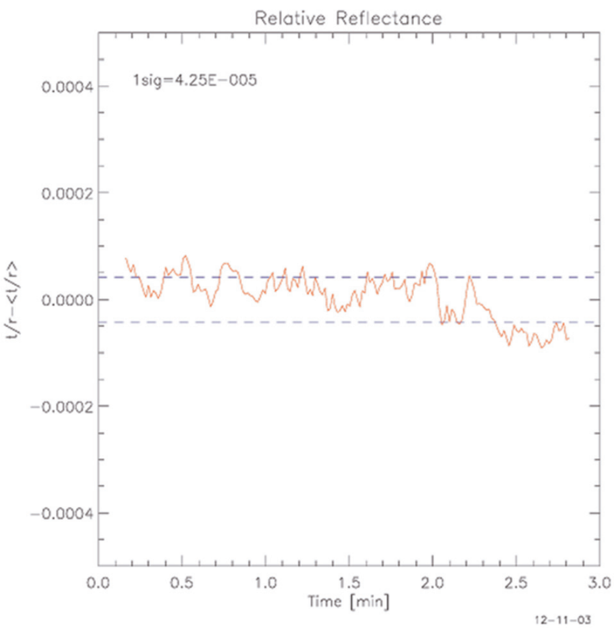


Figure 4: A brief sample of a reflectance measurement showing the very low random system noise.

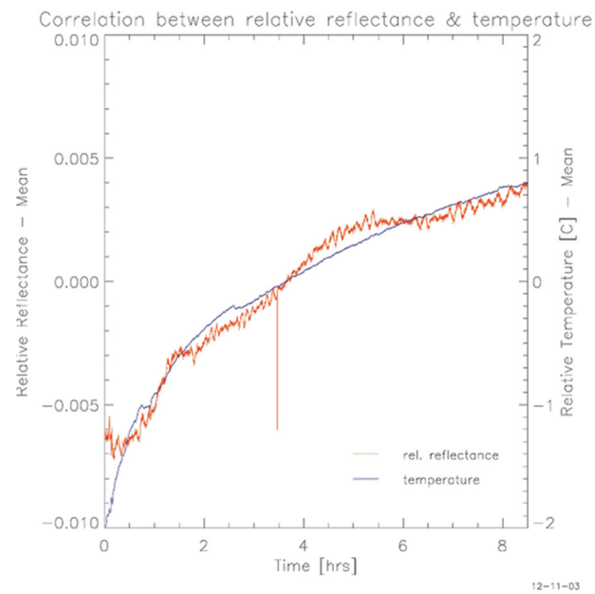


Figure 5. An early data set and illustrates the close correlation with room temperature variability.

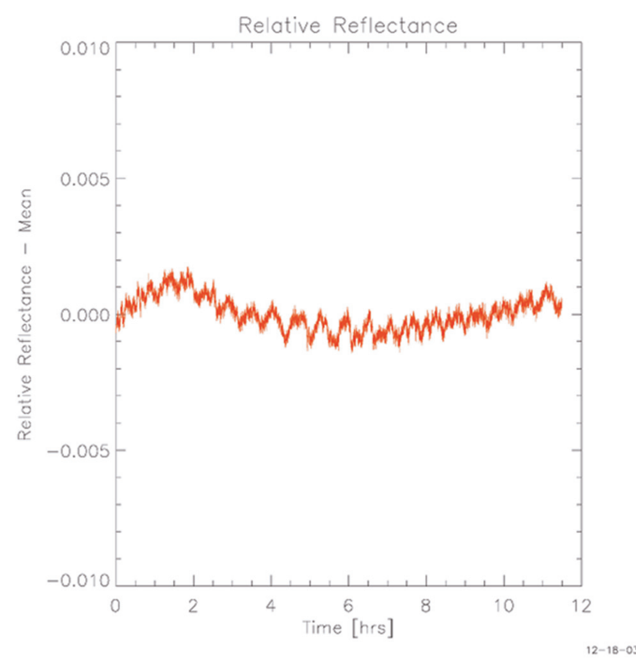


Figure 6. Results following several improvements; the periodic variations are also correlated with room temperature changes but the overall system stability is much improved.

the predicted deviations with aluminum coatings, such as illustrated in figure 2.

Results of the calculations of the effects of amplitude non-uniformity on high contrast coronagraphic systems and our method to correct wavefront amplitude and phase were presented at the 2003 SPIE meeting in San Diego and at the 2003 TPF Expo Workshop. These results are being published in the paper: Bowers, C.W, Woodgate, B. E., Lyon, R. G., 2003, "A Novel Method of High Accuracy, Phase and Amplitude Correction for Coronagraphy", SPIE Proceedings, Techniques and Instrumentation for Detection of Exo-Planets.

Planned Future Work:

We plan to further analyze and reduce the systematic errors in our measurements to produce repeatable, high-precision results necessary for high contrast coronagraphy. At this point, the instrument will be transferred to Goddard and installed for sample testing. A coating fixture has been manufactured and high-quality witness samples (small mirrors 5 angstrom rms surface roughness) obtained. Both gold and protected silver coatings will be produced in the 44-inch diameter system at Denton Vacuum, and measurements will be made at Goddard. We may also be able to extend the measurements to other useful wavelengths, and we plan to investigate a means to extend the correction bandpass of our dual Michelson correction system. The results of these measurements will be published.

Summary:

This project has significant innovative features in two areas of planet-finding: (1) We are proposing and quantifying a means to simultaneously correct wavefront phase and amplitude; and (2) we are building a system capable of measuring reflectance uniformity to unprecedented (but necessary) high-precision levels required for missions such as the Terrestrial Planet Finder, or TPF, and providing the first characterizations of candidate coating materials to this level.

Determining the reflectance uniformity performance of various candidate coatings will allow us to characterize the current state-of-the art, to determine if other than the anticipated angle-of-incidence effects are present at these very low levels, and to select the optimal TPF coatings. And if the uniformity requirements cannot be met, we have proposed one method that will allow on-orbit correction of these errors. Precision reflectance measurements to a level of 10^{-4} are a highly challenging objective, and we have not yet fully realized this goal. However we believe we can still make a significant improvement in our instrument and will be able to produce measurements at the levels shown in figure 1 (reflectance uniformity to about $4x10^{-4}$) to be necessary for TPF coatings.

Characterization of MEMS Deformable Mirrors

Principal Investigator: Sara R. Heap (Code 681)

Co-Investigators: Ray Boucarut (551), Harvey Moseley (685)

Initiation Year: 2003

FY 2003 Authorized Funding: $47,000

Actual or Expected Expenditure of FY 2003 Funding: Swales, approximately $30,000; Advanced Computer Concepts, Inc., approximately $17,000

Status of Investigation at End of FY 2003: To be continued in FY 2004 with funds remaining from FY 2003.

Expected Completion Date: April 2004

Purpose of Investigation:

We are collaborating with Stanford University and the Space Telescope Science Institute (STScI) to develop "MEMS" deformable mirrors (DMs), a technology needed to find Earth-like planets around other stars. MEMS, or Micro Electro Mechanical Systems, is the integration of mechanical elements, sensors and other electronics on a common silicon substrate through micro-fabrication technology. Deformable mirrors are mirrors that can bend or adjust to correct for aberrations and produce sharper images. This is accomplished through the use of a multitude of actuators that push and pull on the mirror. Because an Earth-like planet orbiting at 1 astronomical unit will be more than 10 billion times fainter than its parent star, an optical telescope that can detect it will require a coronagraph to suppress light diffracted by the telescope. The telescope must also have a means of suppressing light scattered by imperfections of the telescope mirrors ("speckles") that would otherwise swamp light from a planet. Building a large, stable, "perfect" telescope is impossible. Hence, attention has been focused on deformable mirrors, which offer the prospect of reducing wavefront errors to less than 0.1 nanometer. This would reduce the brightness of the speckles to a value comparable to that of an Earth-like planet. Goddard's role in this collaboration is to test and characterize the MEMS DMs fabricated by Stanford University. Our goal is to gain practical knowledge about MEMS DMs, the first step in establishing Goddard as a player in developing planet imagers for the proposed Terrestrial Planet Finder.

Accomplishments to Date:

We received four MEMS deformable mirrors fabricated by Olav Solgaard at Stanford University. (STScI's DDF paid for the fabrication costs.) Each of the DMs consists of an array of 5x5 mirror cells, with each cell 180 microns across. We inspected the DMs and found that the first one was damaged in the shipment. The remaining three were numbered and measured with Goddard's MicroXam imaging interferometer. The following table gives a quick summary of our findings on the three undamaged mirrors.

DMs can be segmented or continuous. Segmented DMs are essentially mirrors that are segmented pixel by pixel, with an actuator for each pixel to deform the mirror as needed. Continuous-membrane MEMS DMs are in one piece, with several actuators. Segmented mirrors deform like a skyline, with precise "blocks" of mirror raised. Continuous DMs form sloping tent-like deformations. We have found that continuous-membrane MEMS DMs can be fabricated with actuation capabilities -- that is, they can be readily deformed. However, the surface quality of devices so far is poor: We hope to correct wavelengths (λ) to an accuracy at last 10 times greater than what we can now achieve. More precisely, the "unacuated" (or, deformable) quality of the DM is about 1λ in the unactuated state and $\lambda/10$ with actuation. An improvement of 10^2 is needed for a Terrestrial Planet Finder-precursor mission to search for extra-solar giant planets, and a factor of 10^3 to achieve the quality required by the Terrestrial Planet Finder itself. Also, the devices must be handled and stored with care.

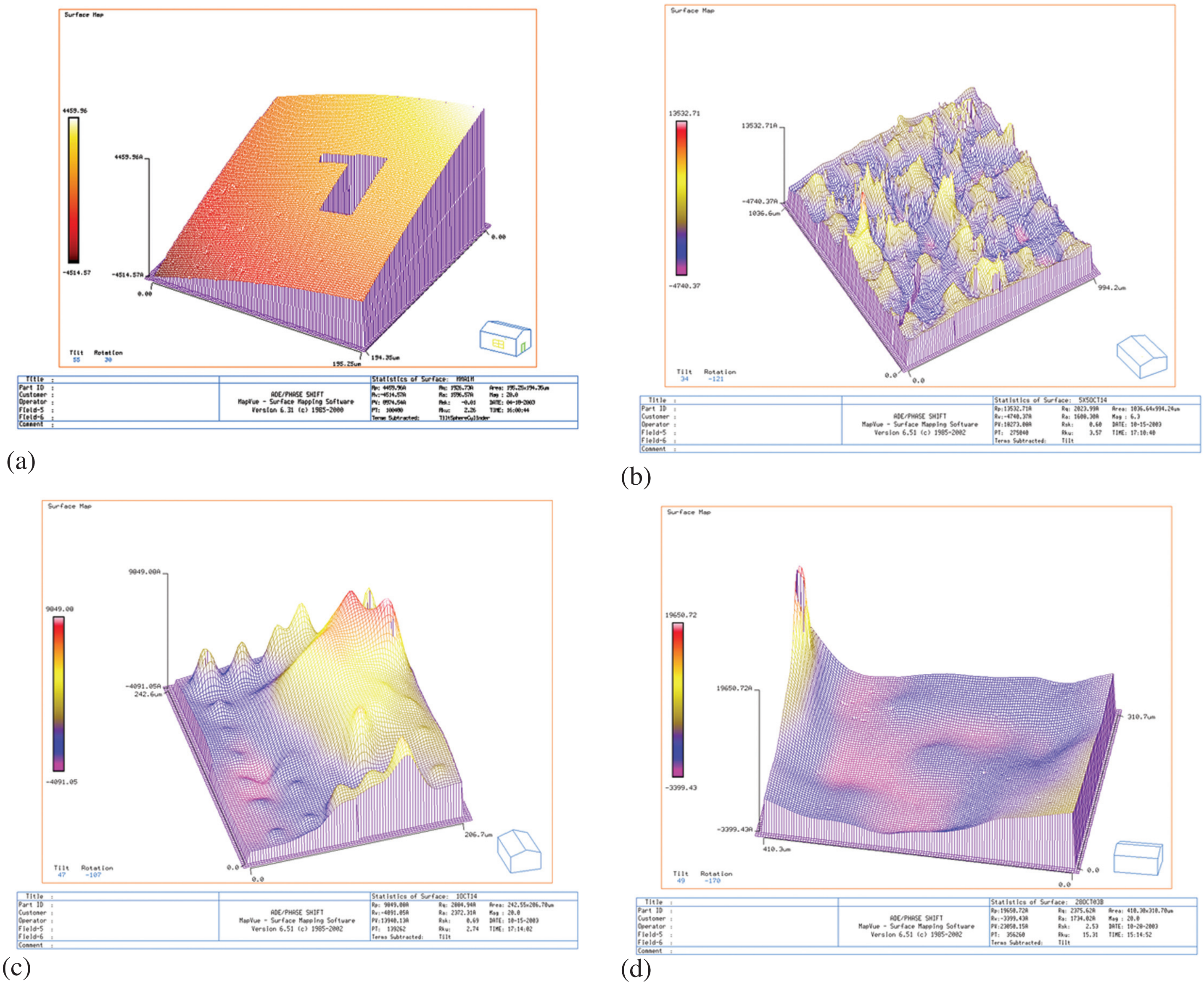


Figure 1. Analysis of three deformable mirrors with Goddard's MicroXam imaging interferometer: (a) SN 1 (segmented DM) - single channel of 5x5 array; the L-shaped hole was made in fabrication; (b) SN 2 - 5x5 array; (c) SN 2 - single cell of 5x5 array; and (d) SN 3 - single cell of 5x5 array.

SN #	DM Type	Condition as received	Surface Quality	Plans
1	Segmented	Unactuateable	Each channel damaged in fabrication	--
2	Continuous	Operable	Severe print-thru	Test actuation at GSFC
3	Continuous	Unpackaged, but potentially operable	Strong warping of array	Return to Stanford for packaging & test at GSFC

Planned Future Work:

We will finish the DDF 2003 project in the next few months. The main task will be to build the electronics for actuation of the channels and to test SN2 and SN3 in actuated states. (SN stands for serial number.)

Summary:

This project deals with MEMS deformable mirrors, which are crucial to high-contrast imagery of astronomical objects but which are currently in the early stage of development. Such mirrors are likely needed in developing planet imagers, such as those for the proposed Terrestrial Planet Finder.

Development of deformable mirrors for large space telescopes is a major technical challenge with no guarantee of success. Deformable mirrors may also present a financial challenge because of the number of actuators involved (tens of thousands). MEMS technology has the potential of cutting the costs down to 1/100th that of conventional DMs, and Goddard could clearly benefit from studying this technology. Our criteria for success are (1) understanding the properties of MEMS deformable mirrors being developed (beyond the state of the art) in order to evaluate their application to planet-finding missions, (2) helping guide design changes in order to accelerate improvements. As for technical risk factors, our major concern has been whether MEMS deformable mirrors – particularly large ones – can be made to be flat. If a DM has curvature, the range of motion of the actuators may not be large enough to correct for wavefront errors. This concern is the largest source of risk in the project, and it turns out to be well justified. We at Goddard have discussed with Stanford University design changes that would help bring about flatness.

Single Electron Transistors as Multiplexers for Large Format Semiconducting Bolometer Arrays

Principal Investigator: Harvey Moseley (Code 685)

Co-Investigators: Christine Allen (553), Thomas Stevenson (533), Ed Wollack (685), Christina Pelzer (NASA Academy)

Initiation Year: 2003

FY 2003 Authorized Funding: $39,000

Actual or Expected Expenditure of FY 2003 Funding: $0

Status of Investigation at End of FY 2003: To be continued in FY 2004 with funds remaining from FY 2003.

Expected Completion Date: September 2004

Purpose of Investigation:

We are developing an amplifier for next-generation microcalorimeters and bolometers, two types of advanced detectors that measure the slight heat or radiant energy induced by incoming photons (light particles) and thus provide a high degree of resolution for studying celestial objects. Amplifiers are needed to “translate” energy deposited by the detected photon. Our amplifier will be multiplexable, able to send several data streams along a single communication line. Semiconducting microcalorimeters represent one type of technology to accomplish this, and they are indeed providing excellent performance in the X-ray Spectrometer (XRS) instrument, which is part of the Japan-U.S. Astro-E2 mission scheduled for a 2005 launch. Goddard is a major player in this mission, which will carry the first X-ray microcalorimeter into orbit. The absence of a credible low-power multiplexed readout for microcalorimeters, however, has resulted in a migration to a new technology for future missions, namely superconducting transition edge sensors. These sensors can use low-power cryogenic SQUID (Superconducting Quantum Interference Device) multiplexers for readout. In this work, we are using one such sensor, a superconducting single-electron transistor (SET), as the readout for an array of frequency multiplexed semiconducting bolometers. We must implement the readout electronics for the SET in a microenvironment of less than 0.1 Kelvin, which is a fraction of a degree above absolute zero. Under this program, we are developing the detector and readout and carrying out the test of the system.

Accomplishments to Date:

During the past year, facilities for test of the SETs were not available due to delays in the lab construction schedule. We used the time to develop necessary electronics to enable us to carry out the measurements when the test facility becomes available. The Radio Frequency (RF) reflectometer for readout of the SET multiplexer was assembled and tested at room temperature by Christina Pelzer, summer Academy intern, and is ready for cryogenic testing. The cryogenic facility for operation of SETs is nearing completion (under separate funding) and should be ready for us to actually test the semiconducting detectors with SET readout by March 2004. Prototype high-impedance semiconducting bolometers have been produced (with separate funding) and have had their initial cryogenic test.

Planned Future Work:

With low temperature ($T < 0.1$ K) test facilities becoming available in FY 2004, we will begin the characterization of SETs, test the multiplexing of SETs, and carry out the initial operation of a semiconducting microcalorimeter using the SET as a readout. At the end of the year, we will be in a position to judge the viability of this approach for future microcalorimeter applications.

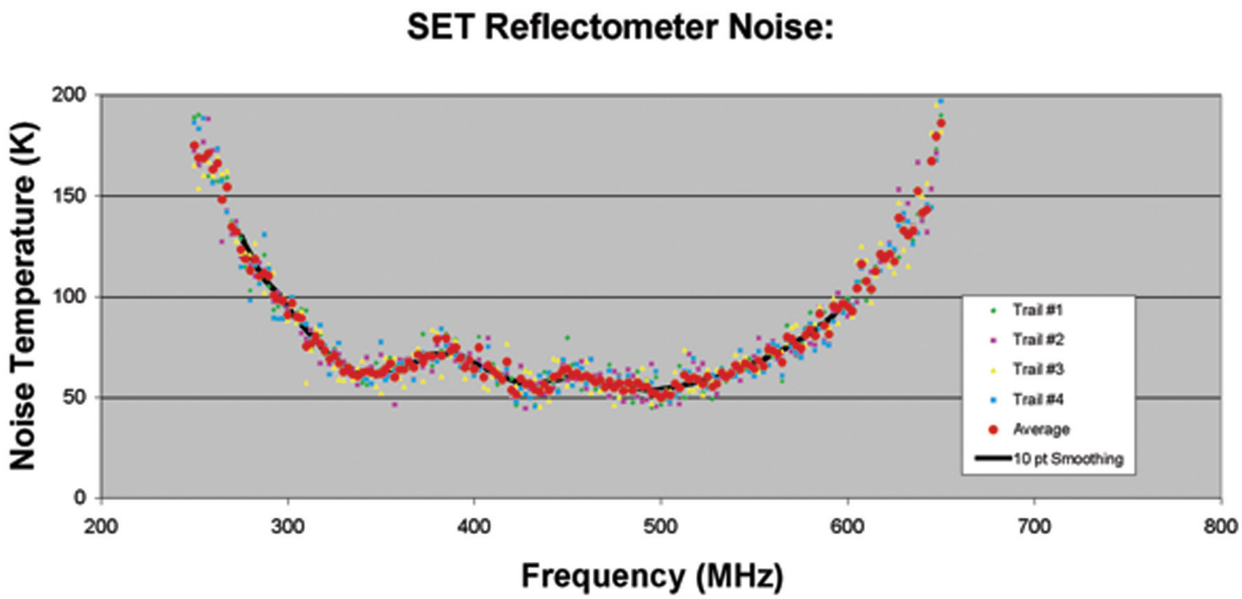


Figure 1: Noise performance of reflectometer over 250 – 700 MHz frequency range.

Summary:

We are developing a technique for reading out large-format arrays of semiconducting bolometer arrays using single-electron transistors, which hasn't been done before. This technology is needed for the next generation of sensitive telescopes for many wavebands, such as infrared and X ray. These telescopes would employ bolometer and microcalorimeters, instruments that measure radiant energy. We are building upon a long experience at Goddard with high-performance semiconducting bolometers and a new capability to produce superconducting single-electron transistors (SETs). Goddard has a strong interest in the production of microcalorimeter arrays for missions such as Constellation X and bolometer arrays for missions such as a cosmic microwave background polarization instrument (CMBPol) and the Single Aperture Far-Infrared Observatory (SAFIR). Specifically, we are developing transition edge sensors arrays, but a strong alternative will provide significant risk reduction. In a successful development, we would demonstrate thermodynamically limited sensitivity in a multiplexed detector. The primary technical risk, which is being removed at this time, is the availability of adequate test facilities. Given test facilities, the primary risk of this readout concept (that is, translating the detected energy into data) is that the multiplexing -- sending multiple data streams along one communication line -- may not be effective enough. The number of detectors read out by a single SET may be inadequate for a practical system.

Dual-Polarization Millimeter-Wave Planar Detector Array

Principal Investigator: Ed Wollack (Code 685)

Co-Investigators: Christine Allen (553), Michele Limon (NRC), Ross Henry (551)

Initiation Year: 2003

FY 2003 Authorized Funding: $70,000

Actual or Expected Expenditure of FY 2003 Funding: Ashlar-Vellum, $500; California Fine Wire (material for polarizing grid), $500; Custom Microwave (waveguide transition), $2,000; Liebmann (optics/test equipment), $10,000; Mathworks, $2,000; McMaster-Carr (tooling/fixture), $3,000; National Instruments (data collection), $1,000; Science Systems Applications, $23,000; Virginia Semiconductor (materials), $20,000; Northrop Grumman (masks), $8,000

Status of Investigation at End of FY 2003: To be continued in FY 2004 with remaining DDF and detector development funds

Expected Completion Date: Late 2004

Purpose of Investigation:

We are developing absorber structures for bolometric detectors that are sensitive to linearly polarized radiation. Bolometers are detectors commonly used by astronomers for studying infrared light, and they usually detect only the energy component of light and not the degree of polarization. Light becomes polarized, or oriented in a particular direction, when it scatters off of dust and gas in deep space (or even off of the hood of a car, causing glare). Polarized light from the early universe provides information about the evolution of galaxies and other structure. Traditionally, instruments have been fitted with a wire-grid device that blocks light polarized in one direction (not unlike polarized sunglasses) and allows the passage of light polarized in another direction. This separation allows for the detection of the individual polarization signals by a pair of individual bolometers. This, in essence, doubles the weight of this portion of the instrument and increases the complexity of the optical design. We are constructing a device, an “absorber,” that replaces the wire-mesh technique. The absorber structure enables both polarization states to be gathered by a single device. The structures under study can be used in large arrays and are compatible with Transition Edge Sensor (TES) processes presently in use. The sensor architecture has three basic layers: a vertical polarization sensor array, a horizontal polarization sensor array, and a tuned reflective backshort. The absorbers on the vertically and horizontally polarized-sensitive arrays will be placed on a silicon membrane approximately one-micron thick by patterning lines of metallization whose thickness is small compared to the electrical skin depth at the wavelength of interest. Upon successful integration of this technique, this effort will provide paths to achieving economically large format arrays with high sensitivity and polarization purity required by CMBPol, SOFIA and other astrophysical missions in these wavebands.

Accomplishments to Date:

We have concentrated on the electromagnetic optimization and the development of high reliability coatings for the absorber structures. Several thin film resistor systems were considered for the absorber (e.g., Ti/Au, Cr/Au, Pd/Au, Ge/Au, and Bi). Of these, disordered alloys of titanium and chrome/gold, most closely approximate negligible thermal heat capacity at thicknesses that result in the desired surface resistivity and have the advantage of an overall parameter insensitivity to temperature. Representative coatings were produced by evaporation and characterized with a Bruker Fourier Transform Spectrometer (FTS) over the millimeter and submillimeter wavebands at room and cryogenic temperatures.The coatings were stable to repeated cryogenic cycling. Accelerated aging tests at elevated temperature enabled derivation of activation energies for the alloy systems under consideration. These studies revealed that the titanium/gold films were the most suitable in terms of the perspective of device reliability, handling, and stability. Similarly, the dielectric properties of representative samples of the approximately 1μm silicon membrane were characterized.

Based upon these inputs, the electromagnetic performance of the absorber structure was analytically studied and subsequently optimized by finite element analysis. See Figure

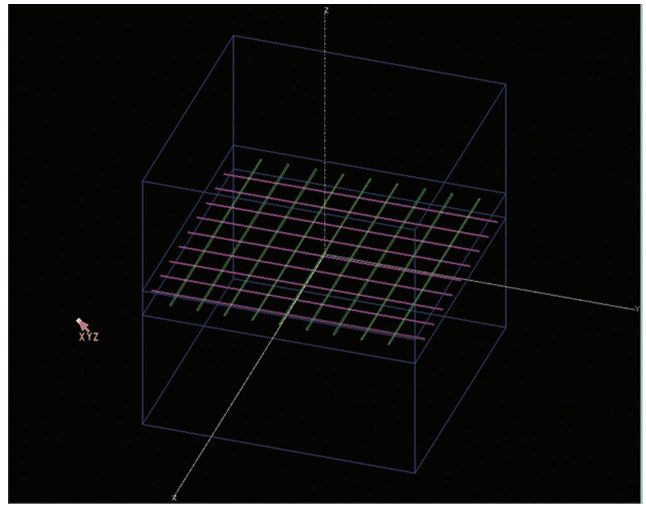
1 for the response of a representative design. In the process of conducting these efforts, it was realized that the cross-polarization response of the absorber structure is intimately linked to the overlap in the incident E-field distribution with the symmetry of the absorber grid in the aperture plane. Application of this concept to absorbers mounted in waveguide structures has revealed that the cross-polarization can be significantly reduced by appropriately tailoring the absorber grid geometry to mimic the dominate mode symmetry. An order of magnitude improvement in this parameter over present structures in use appears possible using this approach.

Planned Future Work:

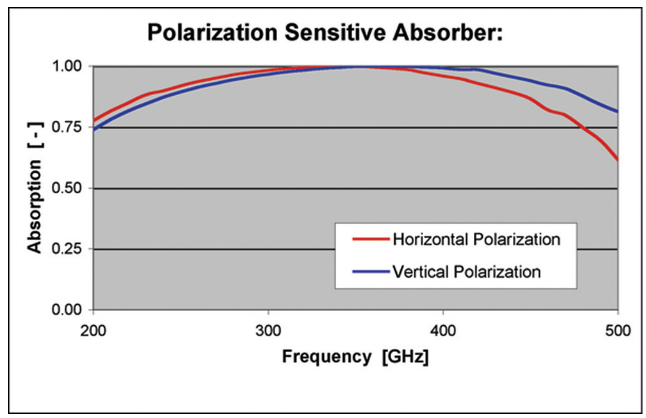
While awaiting the absorber mask sets for the quasi-optical and low-cross polarization waveguide mount prototypes, we are planning further work on the thin films. In particular, heat treatment parameters for the film will be explored as a further means of increasing yield by reducing the film's initial surface resistance creep. In addition, we will investigate the possibility of integrating the witness sample into the absorber structure as a means of providing higher-precision trend data and reducing the associated test costs.Time allowing, the feasibility of tailoring the structure's out-of-band absorptance of the structure will be analytically investigated.

Summary:

Recent improvements in detector technology have sparked renewed interest in extending the imaging and sensitivity capabilities of focal-plane instrumentation at millimeter through sub-millimeter wavelengths. We are developing a polarization-sensitive sensor that is applicable to a variety of millimeter and submillimeter scientific applications. The payoff of this technology to the scientific community is a sensor that is compatible with existing techniques but which offers improved polarization response over existing approaches. The improvements in absorber reliability, stability, and yield will benefit all sensors we produce with related processes. Our criterion of success is creating a device that can be inserted into a detector system and tested in a laboratory or in flight. The technical hurdles include producing parts that work reliably with yield (process control) to allow successful manufacture of large focal plane arrays and cleanly coupling these devices to the telescope optics.



(a)



(b)

Figures 1a and 1b: Dual Polarization Millimeter Wave Sensor Element and Modeled Response. A unit cell $\lambda = 1$mm on a side is simulated at normal incidence with period boundary conditions by finite element analysis (Ansoft Maxwell, High Frequency Structure Simulator). The response of vertically and horizontally polarized absorbers held at a 20μm spacing is presented. Each absorber is formed by 5μm lines on a 100μm pitch with the metallization surface impedance of 18.9/□(e.g., for wavelengths larger than the grid pitch, the effective surface impedance of the absorber is approximately $(100\mu m/5\mu m)(18.9\Omega/\square) \approx 377\Omega/\square$).

Spectral Contrast Enhancement Techniques for the Focal Plane of the Terrestrial Planet Finder

Principal Investigator: Drake Deming (Code 693)

Co-Investigators: Tilak Hewagama (693, UMD), Tim Livengood (693, Challenger Center), Theodor Kostiuk (693), Matt Greenhouse (685)

Initiation Year: 2003

FY 2003 Authorized Funding: $80,000

Actual or Expected Expenditure of FY 2003 Funding: optical and mechanical components, $18,000; electronics and data storage, $6,000; telescope, $6,000; engineering design and data acquisition and analysis, $50,000

Status of Investigation at End of FY 2003: To be continued in FY 2004; no additional funding needed

Expected Completion Date: August 2004

Purpose of Investigation:

The goal of this investigation is to develop a "frequency-switching" technique for enhancing the contrast between an Earth-like extrasolar terrestrial planet and its parent star, as observed using the Terrestrial Planet Finder (TPF) mission. In the visible spectral region this contrast can be as small as 1 part in 10 billion, imposing daunting requirements on TPF coronagraphs that aim to image extrasolar Earth-like planets. If contrast can be enhanced using focal-plane technology, then the requirements on the optical quality of the imaging system can be relaxed to a corresponding degree. Since the cost and risk of these coronagraphs is a strong function of the required optical quality of the large coronagraph optics, the potential payoff of our project is that it can shift some of the performance burden to the focal plane, yielding a leveraged reduction in the cost and risk of the mission.

Accomplishments to Date:

Our work is intended as a proof-of-principle for contrast enhancement by rapidly switching and differencing between two wavelengths. As a proxy for the spectrum of an extrasolar earth, we observe the spectrum of "earthshine" -- that is, the light of the Earth as reflected by the dark side of the Moon. Figure 1 shows the observed spectrum of earthshine from Woolf et al. Note the increase of intensity at the shortest wavelengths due to Rayleigh scattering by molecules in the Earth's atmosphere, and the step-like increase near 720 nm due to increased red reflection by terrestrial vegetation (the so-called "red edge"). We will recover spectral features of earthshine at spatial positions extremely close to the lunar terminator, using rapid optical-frequency-switching. In this way we exploit the natural geometry of lunar reflectance to imitate the situation of an Earth-like planet in close proximity to a solar-type star.

During FY03 we worked primarily on the optimal design of the frequency-switching imaging system. Implementation of the designed system is only now beginning. We experienced long delays due to the availability of FY 2003 funds, which arrived in May 2003, and even longer delays engendered by the transition to IFMP at Goddard.

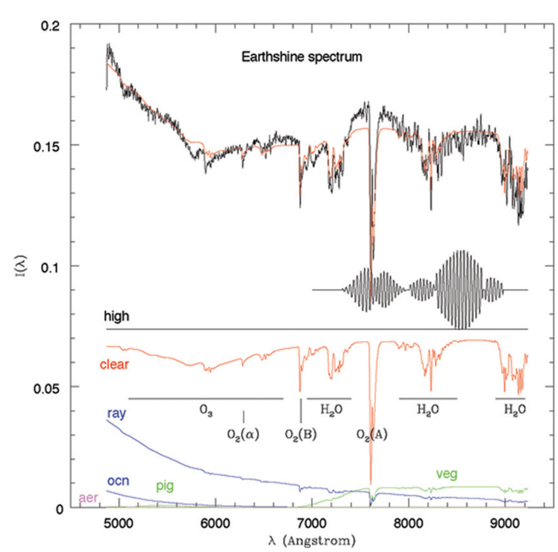


Figure 1. Spectrum of the whole Earth, as revealed by Earth's light reflected from the moon ("earthshine"). Credit: Woolf et al. (2002, ApJ, 574, 430).

However, our first optical components were recently delivered and the first exploratory detection experiments will commence in early 2004.

Planned Future Work:

If our exploratory techniques are successful, we will propose further development under forthcoming NASA research announcements, and development opportunities such as technology programs leading to TPF.

Summary:

Success in our project will be measured by the degree to which we can detect earthshine signatures near the lunar terminator in the presence of direct solar reflectance that is orders of magnitude brighter. Our goal is to enhance detectability by a factor of 1,000 over conventional imaging. The technical risk factors that might prevent success involve potential spectral distortions that may be introduced by the optical complexity of the frequency-switching technique.

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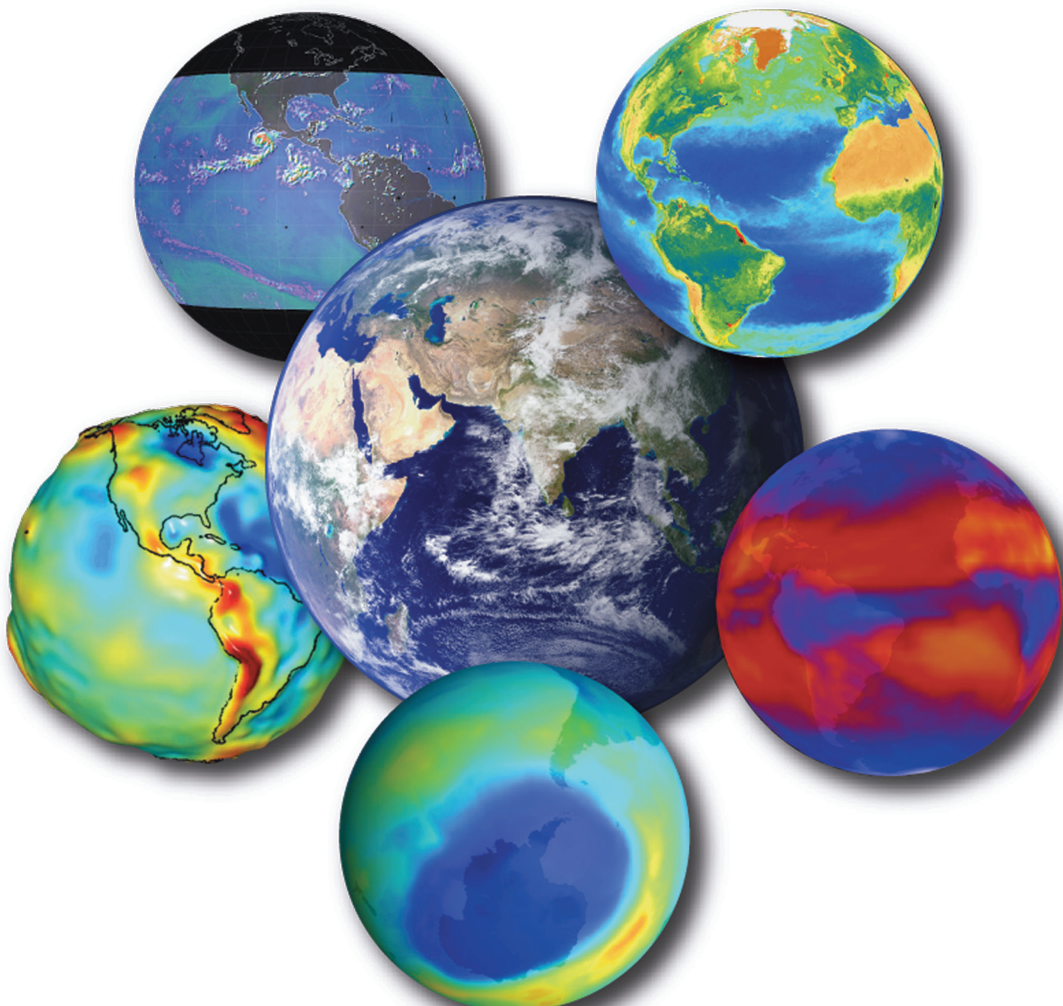


New Lidar Technique for Measuring the Direct and Indirect Effect of Aerosols

Principal Investigator: David N. Whiteman (Code 912)

Co-Investigators: Belay Demoz (912)

Initiation Year: 2002

Aggregate Amount of Funding Authorized in Earlier Years: \$50,000

FY 2003 Authorized Funding: \$50,000

Actual or Expected Expenditure of FY 2003 Funding: In-house, \$20,000; contracts with Welch Mechanical Design, \$10,000; grants for Dr. Igor Veselovskii, \$20,000

Status of Investigation at End of FY 2003: Transition to Other Funding: NASA Radiation Sciences Program

Expected Completion Date: September 2006

Purpose of Investigation:

We are developing a remote-sensing technique that can permit the transformation of aerosol particles into cloud droplets to be studied directly. Aerosols are solid or liquid particles in a gaseous medium. Understanding this aerosol activation process is fundamental to understanding cloud physics processes and for quantifying the effect of aerosols on cloud composition. The technique consists of using multi-wavelength Raman lidar (three wavelengths are emitted to the atmosphere and 7 wavelengths are received) for measuring simultaneously the profile of aerosol physical parameters, such as size distribution and number density, along with cloud physical parameters such as liquid water content, droplet radius and droplet number density.

Accomplishments to Date:

A lidar receiver module that combines together the aerosol and cloud measurements described above has been constructed and tested. Measurements of all necessary signals to permit the combined retrievals of aerosol and cloud physical parameters have been made from the Code 912 Raman Lidar Lab in Building 33. Some of these measurement capabilities have been introduced into the mobile Scanning Raman Lidar that is regularly deployed for field campaigns such as the recently completed AIRS (Advanced Infrared Sounder) Water Vapor Experiment at the Department of Energy's atmospheric test site in northern Oklahoma. An example of these measurements is shown in figure 1.

This figure shows three images of data acquired on November 13, 2003. The cloud scattering ratio, cloud depolarization and cloud liquid water have been simultaneously sampled. The strong scattering observed in the scattering ratio image in the upper left has a peak at approximately 5.8 km. This is the where the depolarization has a minimum. By contrast the depolarization peaks strongly between 4 and 5 km. The liquid water signal shows increases only above 4.5 km where the scattering ratio also increases. The radiosonde showed that the temperature of this cloud was below freezing throughout. Therefore, the interpretation of these images is that there is a layer of super-cooled droplets that is freezing and precipitating. The low depolarization and strong liquid water signals between 5 and 6 km support this interpretation. The low scattering ratio and liquid water signal and the high depolarization indicates the presence of a low concentration of precipitating particles -- that is, frozen virga. Here the liquid water measurements have been used to aid the interpretation of a complex cloud process. We will study this case further and attempt to derive the actual liquid water content and droplet size in the supercooled region.

In addition, the ability to retrieve bi-modal distribution from multi-wavelength lidar data has been developed. This will permit more realistic aerosol size distribution information to be determined using multi-wavelength Raman Lidar. This information will also be of value in sunphotometer comparisons and validation. An example of the bi-modal retrieval capability is shown in figure 2. The figure shows the comparison of several runs of the retrieval code for a given set of input conditions. Three backscattering (1064, 532, 355 nm) and two extinction (387, 607 nm) wavelengths have been used in the simulation.

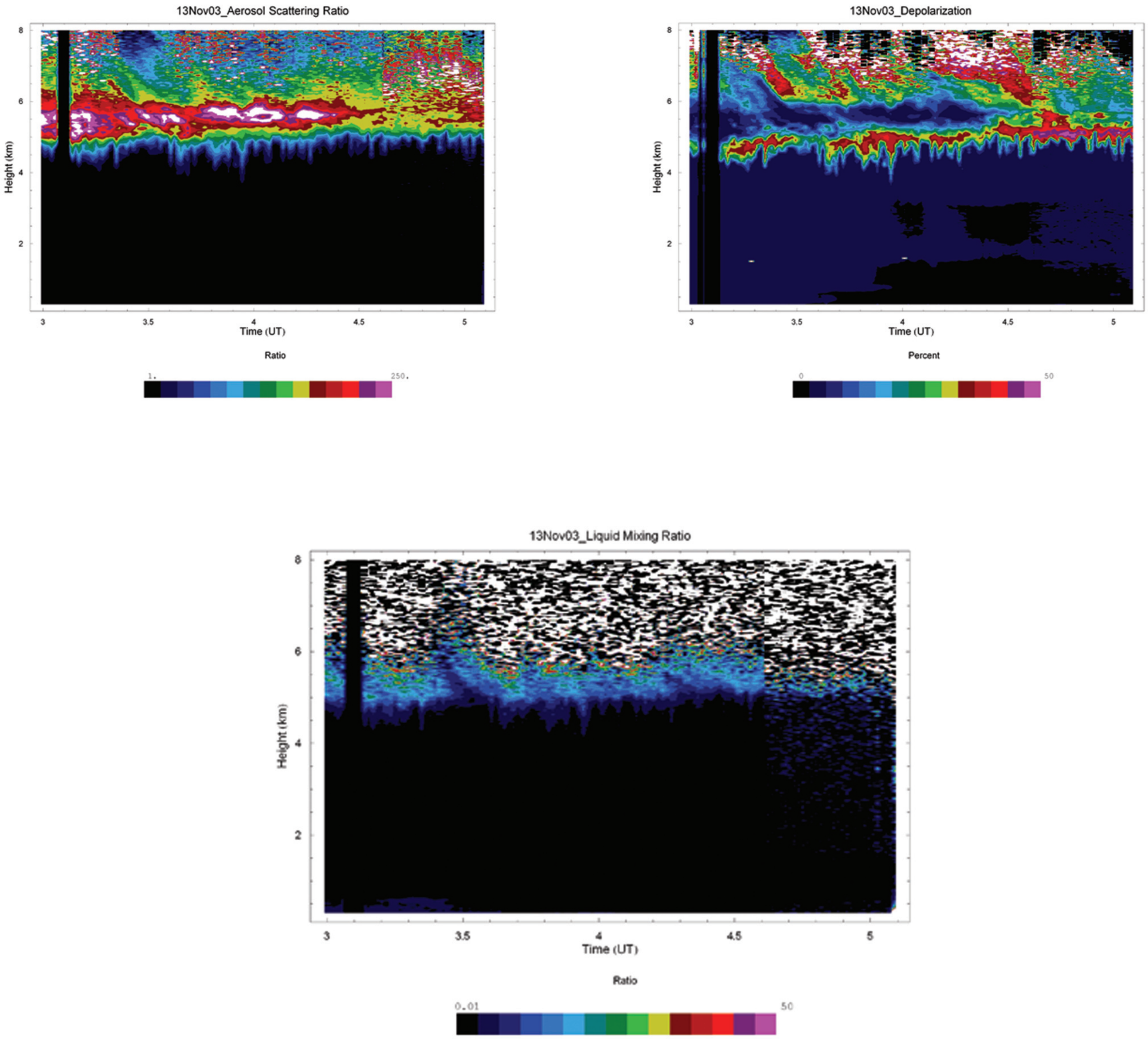


Figure 1. Measurements of cloud scattering ratio, cloud depolarization and cloud liquid water made by the NASA/GSFC Scanning Raman Lidar during the AIRS Water Vapor Experiment in October-November, 2003 in northern Oklahoma. This is an interesting mixed-phase case where a liquid layer is seen to overlie a frozen region of precipitation. The liquid water channel of the SRL is responding strongly in the liquid region of the cloud but not in the frozen region.

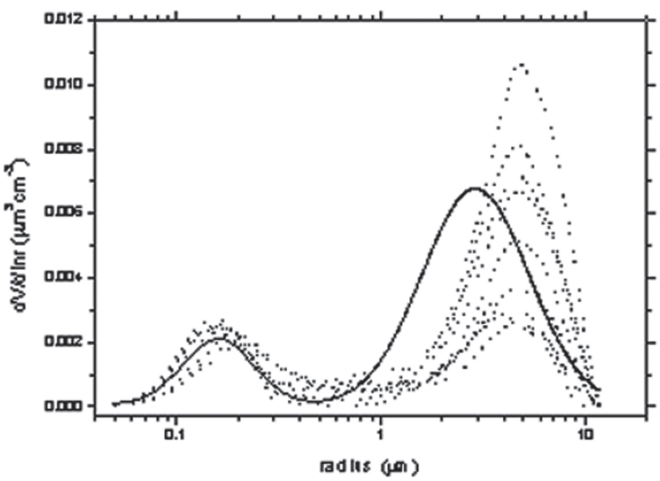


Figure 2. Retrieval of size distribution for m_f=1.55-i0.01 and m_c=1.35-i0. Errors of optical data were 10%. Dotted lines show the scattering of solutions obtained in ten program runs. In the inversion of $3\beta+2\alpha$ data set volume kernel functions are used. Solid line shows initial size distribution.

The differences in the results of several runs of the retrieval code are used to assess the uncertainty in the retrievals.

There have been two publications produced under support of this DDF: (1) Veselovskii, I., A. Kolgotin, V. Griaznov, D. Müller, U. Wandinger, D. N. Whiteman, "Inversion with regularization for the retrieval of tropospheric aerosol parameters from multi-wavelength lidar sounding", Appl. Opt. 18, 41, 3685-3699 (2002); and (2) Igor Veselovskii, Alexei Kolgotin, Vadim Griaznov, Detlef Müller, Kathleen Franke, David N. Whiteman, "Inversion of Multi-wavelength Raman Lidar Data for Retrieval of Bimodal Aerosol Size Distribution", accepted by Applied Optics. There have also been two conference presentations based on the work in this DDF: (1) Retrieval of Tropospheric Aerosol Parameters From Multiwavelength Lidar Sounding, Igor Veselovskii, Alexei Kolgotin, Vadim Griaznov, Detlef Müller, Ulla Wandinger, David N.Whiteman presented at the 21st International Laser Radar Conference in Vichy, France July 2002; and (2) Retrieval of Bi-Modal Aerosol Size Distribution with Multi-Wavelength Mie-Raman Liar, I. Veselovskii, A. Kolgotin,D. Müller, K. Franke, presented at the International Symposium on Tropospheric Profiling, Leipzig, Germany September, 2003.

Planned Future Work:

We have not yet performed measurements of remote aerosol and cloud droplet properties together although we have considerably advanced the individual measurement techniques. We expect to accomplish the combined retrieval of these properties through the support of the NASA Radiation Sciences Program that we have recently obtained for this effort.

Summary:

This is the first attempt to combine lidar remote sensing techniques for aerosol and cloud droplet physical properties. This combined measurement capability offers the potential to study the cloud condensation process directly in a manner not offered by any other remote sensing technique. This can improve knowledge of basic cloud formation processes as well as of the effects of varying aerosol properties on clouds. Goddard has major activities in retrieval of both aerosol and cloud properties from such sensors as MODIS (Moderate Resolution Imaging Spectroradiometer). An ability to quantify the cloud condensation process that could result from this investigation would improve our basic knowledge of cloud physics and the interaction of aerosols with clouds. This improved knowledge of the physical processes underlying these phenomena could then be used to improve the parameterizations used in satellite retrieval algorithms. The main criterion for success of this activity would be the simultaneous measurement of aerosol and cloud droplet physical properties in the atmosphere. No remote measurements of this type have ever been performed, and we are attempting to do it by combining two techniques both of which are relatively new. This entails substantial risk for quick success. We have made significant progress in developing each of the two techniques separately but have not yet been successful in using them together in a single measurement. We will continue that effort under the Radiation Sciences Program support.

Spectral Ratio Biospheric Lidar

Principal Investigator: Jonathan A. R. Rall (924)

Co-Investigators: Robert G. Knox (923)

Initiation Year: 2003

FY 2003 Authorized Funding: $25,000

Actual or Expected Expenditure of FY 2003 Funding: $25,000 for Space Sigma contract

Status of Investigation at End of FY 2003: transitioning to Instrument Incubator Program

Expected Completion Date: completed, transitioning

Purpose of Investigation:

Our project helps address the "missing carbon sink," which refers to the fact that rising levels of CO_2 in the atmosphere do not jibe with what we think we are releasing into the atmosphere through the burning of fossil fuels and other sources. Vegetation sequesters CO_2 and is one possible sink. The purpose of our project is to (1) develop and demonstrate a prototype vegetation index lidar and (2) determine whether practical vegetation index and chlorophyll content can be derived with a two-wavelength lidar operating on either side of the dramatic "red-edge" transition exhibited by all green vegetation. This will allow us to determine how much biomass (trees, plants, grasses, etc.) covers the land. Lidar is analogous to radar with lasers. Exciting molecules in vegetation with a laser causes the vegetation to emit light at characteristic wavelengths. With the current, single-wavelength lidar method of measurement, it is difficult to differentiate between vegetation and rocks. The two-wavelength method reveals the "red-edge", which refers to lower-energy "reddened" light emitted by vegetation but not by inorganic material. We are also investigating power scaling using fiber optic amplifiers to boost power levels to those needed for high-altitude aircraft or possibly orbital missions.

Table 1. System Specifications

	Red	Near IR
Laser Power	40 mW	70 mW
Wavelength	665 nm	781 nm
Pulse length	4 μS	4 μS
Pulse repetition	4 kHz	4 kHz
Photon detection	70%	50%

Accomplishments to Date:

A low-power prototype lidar was assembled and tested. The prototype lidar uses semiconductor laser diodes operating at 660 and 780 nm to transmit the visible and near IR light to the target (trees), a 20-cm telescope to collect the backscattered light, a dichroic beamsplitter to separate the two received wavelengths and two photon counting detectors to detect the received light. The output pulses of each detector are recorded by a multichannel scalar connected to a desktop computer. Figure 2 shows a picture of the low-power, demonstration system and the system specifications are listed in table 1.

Measurements over a horizontal path have been made from the penthouse laboratory on the roof of Building 22 to a bank of trees approximately 360 meters away. The timing of this measurement campaign, early October through November was picked to coincide with the changing of color, i.e loss of chlorophyll, of the deciduous vegetation. To calibrate the instrument, that is normalize the data to the transmitted power and determine the receiver losses at each wavelength, a small spectralon panel was mounted to a nearby roof and measurements were made to it. Spectralon, which is a particularly good reflector, demonstrates very nearly flat reflectance over our wavelength range of interest, making it ideal for calibration purposes.

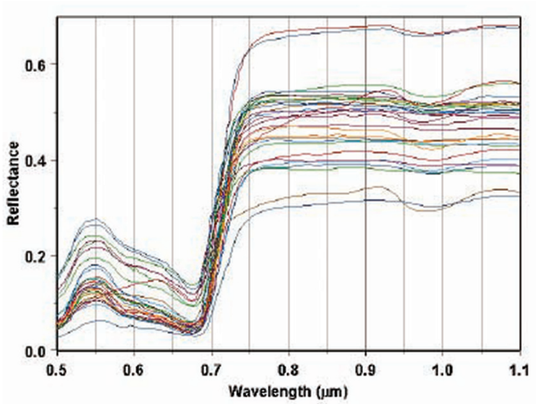


Figure 1. Spectral reflectance of vegetation

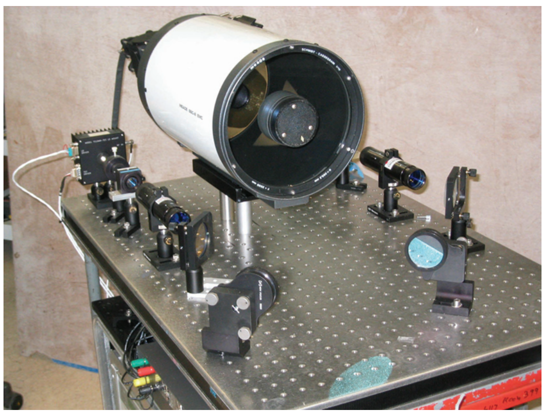


Figure 2. Low power Spectral Ratio Biospheric Lidar system.

Figure 3. View of trees used to demonstrate spectral ratio technique.

Measurements to Building 5 high bay or the spectralon panel were made at the beginning of each session and then again at the end, after vegetation measurements. Figure 4 shows data taken on the night of October 9 and then again on the night of November 20. Each plot contains a close-in return from the side of Building 5 (used as a reference target prior to acquiring the spectralon panel) and signals scattered from the bank of trees shown in figure 3. The deciduous trees had not changed colors by October 9 and an examination of the red channel data confirms that. The green leaves have significantly absorbed the red laser signal and strongly reflected the NIR, almost 60 times stronger than the red. The signals from the side of Building 5 are similar in strength between the red and the NIR channels.

On November 20, the trees had completely changed color and lost a significant amount of foliage. The calibration signal from the spectralon target was much stronger than the earlier measurements to the high bay of Building 5 and therefore has expanded the vertical scale. However, it is clear from figure 4 that the signal from the trees is nearly equivalent between the red and NIR channels indicating that the reflectance is uniform between the two wavelengths.

Robert Knox has prepared a patent disclosure. Two journal articles are being planned. Papers are in preparation for both the International Laser Radar Conference and the International Geoscience And Remote Sensing Symposium. Jonathan Rall received an Earth Science Directorate Special Act Award for co-developing this technique.

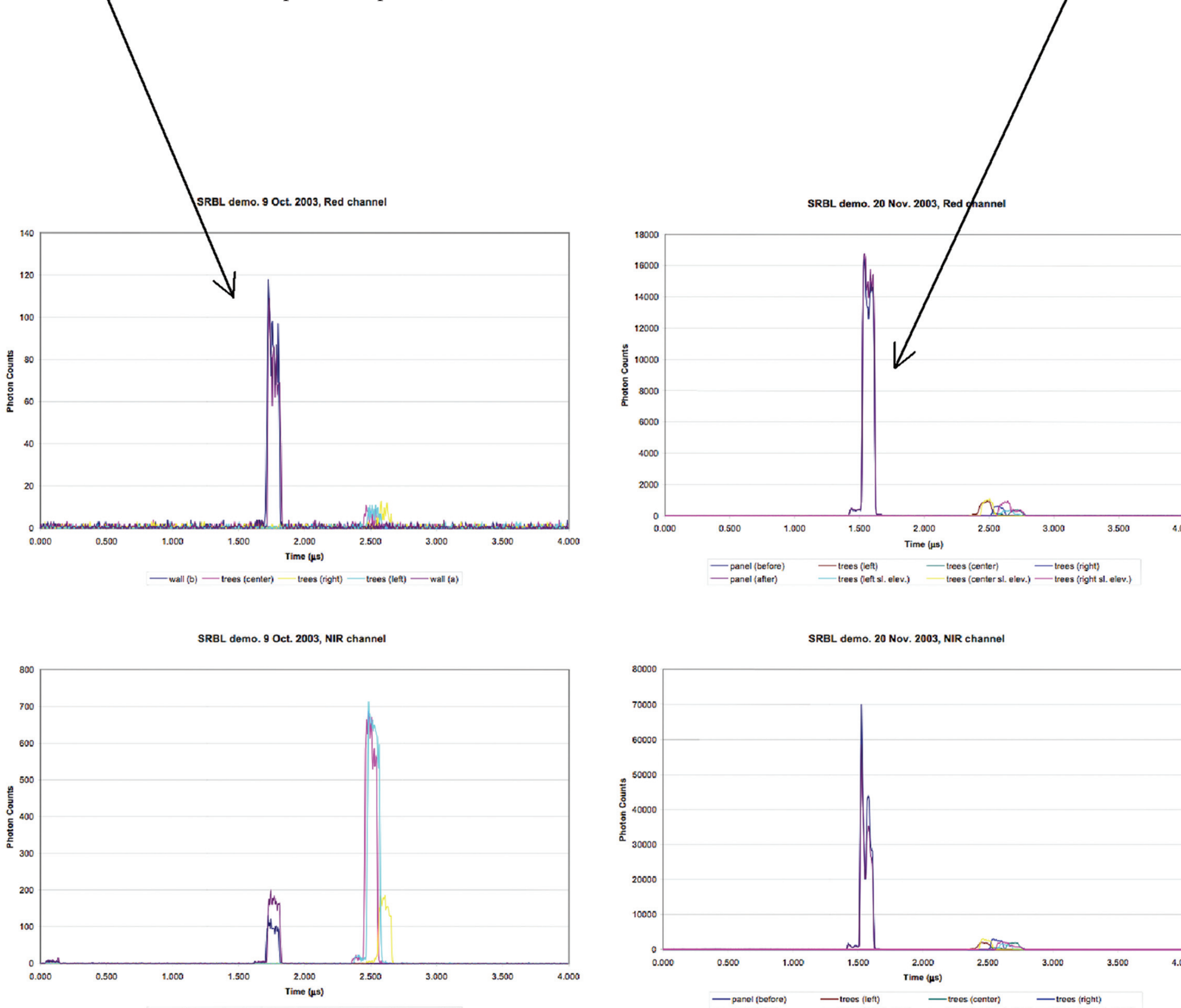
Planned Future Work:

We plan to demonstrate higher-power laser sources (1-5 Watt CW) at 660 nm and 780 nm using fiber optic amplifiers. We will also investigate advanced modulation techniques (pseudo noise codes, pulse position modulation) to make use of high average power fiber amps, and we will prepare a proposal to the NASA Code Y Instrument Incubator Program. The call is expected sometime during Summer 2004.

Summary:

This project's innovative features are the use of lasers to measure active vegetation index and the use of laser diodes and fiber amplifiers as laser transmitters. For NASA and Goddard, this may lead to a new, innovative measurement technique that is much less sensitive to atmospheric effects, which currently make such measurements difficult. Our criterion of success is the successful transition to the Instrument Incubator Program (IIP) and aircraft demonstration using higher power transmitters. One technical risk factor that might prevent achieving success is generating high power laser light at 660 nm using Raman Amplification in transport fibers and frequency doubling.

Figure 4. Measurements to side of Goddard building 5 (Oct. 9), spectralon panel (Nov. 20), and trees.



A Laser Diode, Fiber Amplifier - Based Altimeter Laser Transmitter For High Accuracy Planetary Surface Mapping

Principal Investigator: D. Barry Coyle (Code 920)

Co-Investigators: none

Initiation Year: 2003

FY 2003 Authorized Funding: $45,000

Actual or Expected Expenditure of FY 2003 Funding: $25,000 for 1-Watt diode pumped Yb doped fiber amplifier; $15,000 for pulsed 1047nm single frequency external cavity diode laser; $5,000 for assorted coupling and isolation optics

Status of Investigation at End of FY 2003: Proof of concept demonstrated, transitioning to Instrument Incubator Program proposal in 2004 for further work.

Expected Completion Date: Spring 2005

Purpose of Investigation:

In this 2003 DDF effort, we are developing an alternative to a diode-pumped solid-state laser as a transmitter for aircraft and future spacecraft-based terrain-mapping altimeters. We are constructing a novel, high-repetition-rate laser transmitter in conjunction with AdvR Inc., manufacturer of custom wavelength single frequency diode lasers, and Keopsys Inc., sole manufacturer of V-groove pumped Ytterbium doped fiber amplifiers. Essentially, the wavelength, pulse width, repetition rate, and pulse energy of this system will be tunable. This would allow us to conduct a variety of diverse topographical mapping -- for example, "flat" ice sheets, dense forests, and jagged mountains -- using one instrument on an aircraft or satellite at any altitude. Currently, altimeters are not this flexible, and scientists are limited by the instrument in the types of mapping they can perform. A tunable system would allow for seamless mapping from one terrain to another. Tunable repetition rates between 10-100 kHz, for example, would enable "high density, small footprint altimetry," which means that an aircraft flying at a constant speed could send more laser pulses to the ground in certain regions to attain more detailed information from complicated terrain. Because of its variability, this system can be adapted to other uses outside the field of remote sensing, such as laser-marking and various types of spectroscopy. Based on a successful 2002 DDF project, "A New 1064 nm Diode Source for Injection Seeding High Power Remote Sensing Laser Transmitters," we plan to employ this highly stable continuous-wave (CW) laser source at virtually any wavelength between 970 and 1080 nanometers as a viable alternative to lower-repetition-rate diode-pumped laser sources.

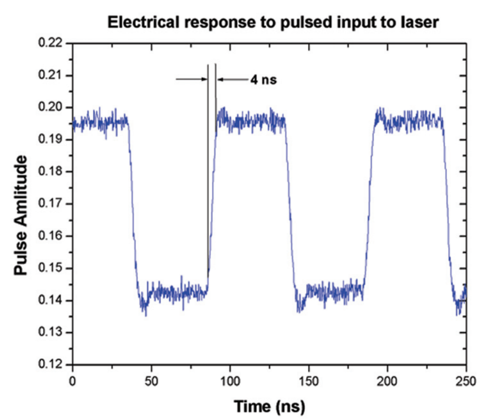


Figure 1. The first test data taken showing a 2 ns rise time.

Accomplishments to Date:

The success of this project now means that a wide range of laser altimetry mapping parameters can be achieved, depending upon the desired science or type of application. Repetition rates between 10 - 100 kHz are sought for high density, small footprint earth and planetary altimetry. Currently, such a system does not exist in a conductively cooled, efficient portable package. The heart of the system is a custom diode laser, tuned to wavelengths of 1047 nm or 1064 nm; those of commonly used altimetry solid state laser hosts. This is achieved with a Bragg grating written in an electro-optically tuned KTP (Potassium Titanyl Phosphate) waveguide. This feature, combined with thermoelectric cooling on the diode laser and the KTP chip, provides an ultra-stable, single-frequency source. The absolute stability characteristics have yet to be measured, as this feature is not an important

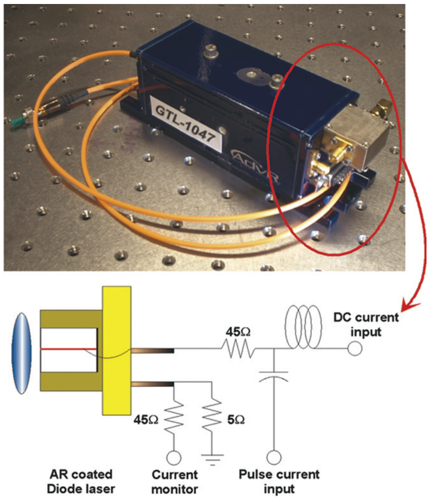


Figure 2. Final enclosure of the pulsed, KTP tuned diode laser. Fiber coupling, a new feature on this design, is currently being implemented and tested.

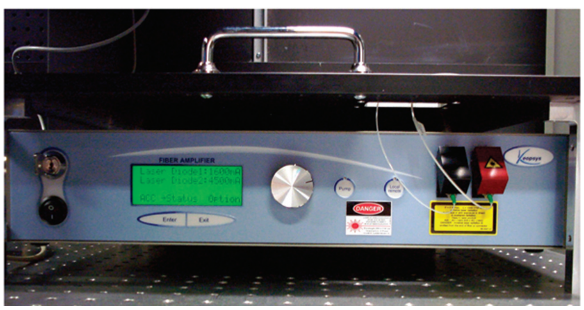


Figure 3. Our diode pumped Ytterbium fiber amplifier, mounted with an integrated breadboard for portability or aircraft installation.

aspect in laser altimetry and mapping. What is important is the ability of this laser to produce Gaussian pulse widths on the order of 2 to 10 ns. A pulse-forming network has been incorporated in the diode package. Figure 1 shows a typical square wave driving output, shown as proof of concept, but the fact that the rise times are short (4 ns) is evidence that even shorter rise times are possible with a faster driver. The amplifier is capable of 1 Watt CW output from 1040 nm and 1100 nm. At 10-100 kHz diode rep rate, we should achieve 100-10 μJ pulses, respectively.

Both major components, each a custom improvement in a relatively new product, were delivered by October 2003. However, the pulsed diode source suffered ESD damage on transit. In order to produce proof-of-concept in this project, we retuned an existing diode pumped Nd:YLF laser to simulate the diode source. With this setup, we were able to achieve gains on the order of 3dB or more with repetition rates between 10-100 kHz. A publication is being prepared for submittal to Applied Optics in early 2004.

Planned Future Work:

A proposal is also planned for submittal to the Instrument Incubator Program in the spring of 2004 as a part of a complete aircraft-based high-density surface and vegetation mapping system.

Summary:

The most innovative aspect of this work was that we had an all solid-state system and no liquid cooling. We also had a completely tunable in-repetition rate and pulse width to fit the relevant science application. This feature does not exist in the field of laser altimetry. Currently, altimeters are not flexible, and this limits the diversity of mapping that can be done during any single flight or satellite mission. Pending a successful Instrument Incubator Program (IIP) award, this will constitute the only completely tunable mapping system, which positions Goddard well in this field. Our project may lead to major advances in topographic mapping. One success criterion was met in that we demonstrated proof of concept. We now move forward to the IIP. The major technical hurdle has been the robustness and packaging of the tunable diode source. All the data gathered proves that the successful diode delivery will work.

Multi-tuned Active/Passive Antenna Element Characterization

Principle Investigator: Larry Hilliard (555)

Other Investigators: Ross Henry (551), David Thompson (NASA Academy), Thomas Pichel (LASP Intern)

Initiation Year: FY 2003

Funding Authorized for FY 2003: $17,000

Actual or Expected Expenditure of FY 2003 Funding: Flomerics, $4,000; LASP, $3,600; Emerson and Cuming, $400; Arlon MED, $500; Rogers Corporation, $1,600; Mouser Electronics, $200; Minicircuits, $300; Modular Components National (MCN), $1,400; Code 541 outgassing tests and additional work at MCN, approximately $5,000.

Status of Investigation at End of FY 2003: Proposed to be continued in FY 2004 with additional DDF funding and integration of DDF designs with Internal Research and Development, Advanced Technology Initiatives Program, University Nanosat Program, and Unmanned Aerial Vehicle development items.

Expected Completion Date: August 2004

Purpose of Investigation:

The purpose of this project is twofold: to design a single multi-tunable antenna (MTA) patch that resonates at two specific frequencies; and to design, test and characterize a new microstrip patch array design. These devices will help enable space-based studies of soil water moisture around the globe. We are attempting to prove the feasibility of combining radar and radiometry for remote sensing -- that is, combining active and passive measurements, which hasn't been done before from space. The radar element involves bouncing a beam from the spacecraft off the Earth's surface (radar backscatter). Radiometry involves detecting the natural radio waves emitted by surface water (hydrological brightness temperature), analogous to using night-vision goggles to "see" infrared radiation emitted by objects. Such measurements can be done from airplanes but require many flights for reasonable analysis of soil moisture. Yet satellites, farther up than airplanes, require larger apertures (in our case, apertures are antennae) to attain suitable resolution. To reduce the need for a larger aperture in space, we are taking advantage of new Radar and Synthetic Thinned Array Radiometer (RadSTAR) elements, which we will ultimately configure as a synthetically thinned array for a passive radiometer at 1.413 GHz and feed separately for active radar operation at 1.26 GHz. This is why we require a physical (hardware) patch that resonates at these two frequencies. The microstrip array would extend this capability from one detector to many. Inexpensive but highly relevant platforms, such as the University Nanosat Program (UNP) and Unmanned Aerial Vehicles (UAVs), can advance our lightweight low-complexity design. The spaceflight RadSTAR design will serve the purpose of combining the two systems using the same antenna for both operations, greatly reducing the size, complexity, and cost of the antenna array used.

Accomplishments to Date:

Our current array design consists of an 8x10 array optimized for operation at 1.26 GHz. It will be used alongside an Electronically Scanned Thinned Array Radiometer (ESTAR). The L-Band Imaging Scatterometer (LIS) array elements have a requirement to achieve >10 dB return loss over an 18 MHz bandwidth (BW). Using design leads and tips obtained from ProSensing (LIS antenna) and Flomerics, the developer of the Microstripes software, we successfully modeled the LIS antenna element and broadband (BW=90 MHz with return loss > 10dB) patches using a U-slot design. This gave us five times the bandwidth of the LIS antenna patch at both our frequencies of interest. Based upon the broadband element design, the 2003 research focused on optimizing the beam efficiency at the radiometer frequency and the best available beam efficiency at the radar frequency.

From these U-slot models, we fabricated an MTA element with the most promising commercial-off-the-shelf (COTS) design materials. For the lightweight UAV application, a sandwich of copper-clad microporous polymeric core material called Foamclad 100 was made around the Emerson and Cuming's product ECCOSTOCK PP-2.

Figure 1 shows the return loss measured on the narrow band L-Band Imaging Scatterometer patch versus the RadSTAR

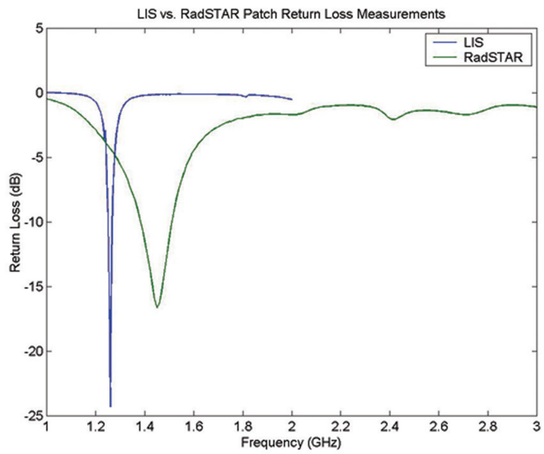


Figure 1. The return loss measured on the prototype "foam" patch.

Figure 2. The prototype "foam" patch in the anechoic chamber.

patch that covers a wider bandwidth. Figure 2 is a photograph of the prototype RadSTAR patch that was tested in the anechoic chamber . Figures 3 and 4 show the co-polarized and cross-polarized beam patterns on the actual antenna as tested at both the radiometer and radar frequencies. Unique active and passive matching circuits makes it feasible to compare a LIS element with a new element utilizing only COTS materials, significantly increase the performance (BW), and lower the areal density for low-mass application requirements (such as suborbital UAVs). Table 1 shows that the dielectric sandwich mass is much less (>10x) in comparison to RT/Duroid 6002. (RT 6002 will be used for the nanosat design because of superior outgassing and thermal properties required for the orbital environment.)

The innovative nanosat design will be a "free space" sandwich. The foam prototype antenna can be used as a starting point to model because the dielectric constant of ECCOSTOCK PP-2 material is εr =1.03. The mechanical requirement to separate the top layer of the sandwich from the bottom layer is met by a ring of space grade dielectric RT 6002, εr =2.94. The foam's relative permittivity is close enough to free space or εr=1 so that the geometry of the patch continues to exhibit the broadband characteristics of the foam sandwich. The resulting far field pattern from the ring is still > 99% efficient in the main lobe but there is a shift in boresight in the asymmetric axis and a lower frequency where peak power is realized.

Planned Future Work:

Based upon these 2003 DDF results, the next phase of the research will focus on developing feed circuits and array spacing for these antenna elements. The proven bandwidth and mass properties of these designs and materials will then be utilized in the nanosat space flight system. The literature on U-slot patches and the modeling thus far also suggest that we must be concerned about the off boresight cross-pole component.

Ultimately, we aim to demonstrate that commercial-off-the-shelf design materials can be used to inexpensively build antennas that approximate free-space permittivity, enabling remote sensing of soil moisture levels globally. Our foam/free-space sandwich is innovative and doubly valuable because it can be used to minimize the dielectric backing structure but still enable NASA to rapidly prototype with space-grade materials. Low-mass Advanced Technology Initiatives Program(ATIP) receivers are already baselined for the nanosatellite mission of about 0.8 kg per module. A lightweighted version of the LIS radar electronics is being developed for a Small Business Innovative Research (SBIR) program, and this lightweight wing antenna has a large potential payoff. It may enable an active/passive hydrology mission using a fleet of low cost UAVs. A mesh ground plane can further reduce the overall mass of really large antennas required for space. The stacked patch, the bandpass filter antenna, and the annular ring antennas are candidates for future modeling activity. We have succeeded in designing and prototyping a wideband antenna patch tunable in this range. Making this broadband design into an array is a technical risk that may limit its application due to array spacing, the aspect ratio of the patch, and the off-boresight cross-pole isolation.

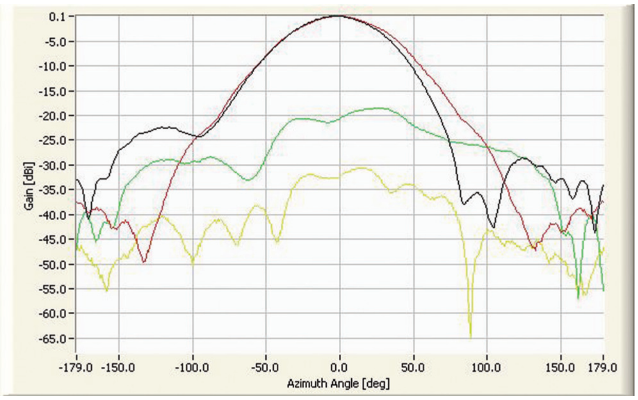


Figure 3. The co- and cross-polarization beam patterns of the prototype patch at the radar frequency (1.26 GHz).

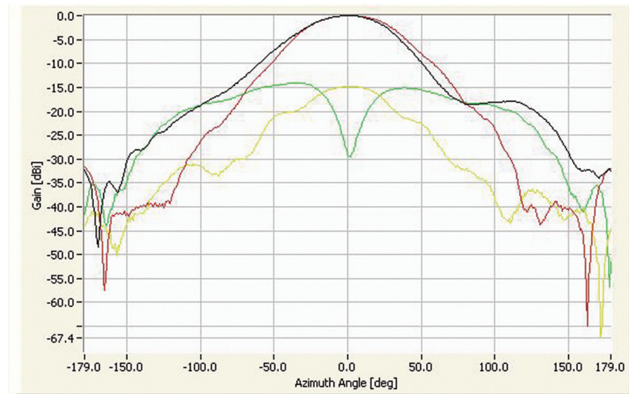


Figure 4. The co- and cross-polarization beam patterns of the prototype patch at the radiometer frequency (1.413 GHz).

Summary:

We are laying the groundwork for a novel method of remote sensing to measure soil moisture from space. This involves combining radar and radiometry -- that is, combining active and passive measurements. Our approach strikes a balance: Currently, airplanes can make such measurements but require many flights to collect enough data for reasonable analysis. Satellites could collect these data; but, higher than airplanes, they require larger apertures (antennae) to attain suitable resolution. We are developing a means to reduce the physical dimensions of the antenna, which requires a sophisticated patch to "tune" the two different frequencies used by the radar and radiometry. This would enable an active/passive hydrology mission using, for example, a fleet of low cost Unmanned Aerial Vehicles, a clear benefit to Goddard and NASA. Our success criterion was met at L-Band frequencies for radar and radiometry. That is, we designed and prototyped a wideband antenna patch tunable in this range. Making this broadband design into an array is a technical risk that may limit its application due to array spacing and other physical limitations that could result in cross-polarization noise, sort of like static. However, we have ideas on how to minimize this risk.

Table 1 – Comparison of Mass in Dielectrics modeled in DDF antenna elements

ECCOSTOCK PP-2 Thickness	0.64
Foam Clad Thickness (cm)	0.09
Groundplane length and width (cm)	30.48
Volume Foamclad 100 (cc)	84.95
Foam Clad Specific Gravity (g/cc)	0.35
Mass of 3 layer foamclad /ECCOSTOCK sandwich per 12"x12" prototype (grams)	*59.47*
6002 mass same dimensions (grams)	*595.04*

Analysis of In Situ and Remote Sensing Aerosol Absorption Data

Principal Investigator: Yoram Kaufman (Code 913), J. Vanderlei Martins (913, UMBC)

Co-Investigators: none

Initiation Year: 2002

Aggregate Amount of Funding Authorized in Earlier Years: $60,000

FY 2003 Authorized Funding: $25,000

Actual or Expected Expenditure of FY 2003 Funding: $25,000 for UMBC/JCET contract; $5,000 in-house

Status of Investigation at End of FY 2003: completed

Expected Completion Date: completed

Purpose of Investigation:

Our main objectives were (1) to demonstrate experimentally a means to measure, from space, aerosol absorption over the ocean sun glint, (2) to develop in-situ validation strategies for aerosol absorption measurements, and (3) to improve our basic knowledge of aerosol absorption properties. Aerosols are solid or liquid particles suspended in a gaseous medium. Measuring black carbon aerosols and other dark material over a dark, blue ocean can be difficult. Thus, we took the approach of viewing this over bright sunlight, or total reflection on the water, which provides the contrast we need to "see" the aerosols. Aerosols can take the form of naturally occurring dust (for example, sand from deserts), pollution, or smoke from forest fires and volcanic activity. The level of aerosol absorption effects the global climate, yet little is known of its properties. If aerosols are strong absorbers of sunlight, than this inhibits cloud formation, warms the atmosphere, and increases the rate of global warming by up to 50%. Yet if aerosols are weak absorbers, then this decreases the rate of global warming by 50%. In the future, some countries will be producing fewer aerosols while other countries will produce more. Our work is an early step in predicting future climate changes on the scale of 50 years.

Accomplishments to Date:

Among the accomplishments obtained as part of this DDF effort, we can emphasize: the data analysis of aerosol absorption over sunglint using the MODIS-AERONET combination; spectral measurements of aerosol absorption from the ultraviolet to the near infrared (350 to 2500nm) for several aerosol types; instrumental developments on the multiple reflection cell prototype for the measurement of aerosol extinction and scattering properties; and the development and application of a single path extinction cell for the measurement of aerosol extinction in the United Forest Service Fire Facility in Montana.

The experimental validation of the sunglint absorption retrievals was attempted as part of the data analysis of the CLAMS (Chesapeake Lighthouse & Aircraft Measurements for Satellites) aircraft experiment, and the main conclusion was the requirement of better characterization of the scattering properties of aerosol particles in order to produce an accurate measurement of the aerosol absorption properties. In terms of satellite remote sensing, this better characterization can be obtained by measuring polarized radiance in multiple angles. During CLAMS, the RSP (Research Scanning Polarimeter) instrument obtained such data set, and the data analysis is being performed by NASA GISS. We have also attempted another strategy, combining ground-based remote sensing from AERONET and sunglint measurements from MODIS (Moderate Resolution Imaging Spectroradiometer) on the Terra satellite. The combination did provide reasonable retrievals of aerosol absorption over the ocean sunglint but it did not reproduce completely the measurement expected from the satellite. These results are being used in the development of the Glory satellite mission, supposed to fly with a multi angle polarimeter system capable of characterizing the absorption and scattering properties of aerosol particles with high accuracy.

A multiple reflection extinction cell prototype has been built as part of this effort and is expected to be used for measuring scattering and extinction properties of aerosol particles dur-

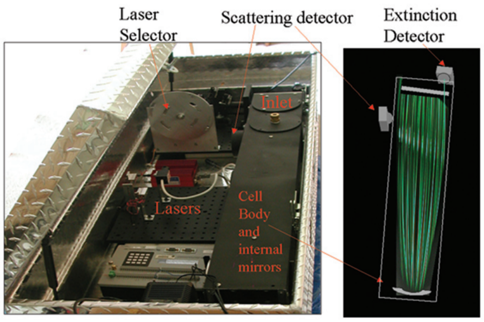


Figure 1. The multiple reflection cell prototype built as part of this DDF effort. The right figure shows a real picture inside of the cell with photons from the multiple reflected beams being scattered by the aerosol particles inside the cell.

ing field campaigns for diverse aerosol types and different locations. The *difference* between the extinction and scattering coefficients corresponds to the absorption coefficient. The *ratio* between scattering and extinction is the single scattering albedo, considered to be the main uncertainty in the climate direct radiative forcing by aerosol particles. The single-scattering albedo is a very difficult property to measure, and most of the available techniques have important limitations and accuracy problems. The multiple reflection cell prototype that we built corresponds to a 100-meter path length obtained by about 150 reflections of laser beams with different wavelengths inside a 850-mm cell. Photodiode detectors measure the reference laser beam, as well as the beam exiting from the cell, and a photomultiplier module connected to wide field of view optics measures the scattering coefficient of the aerosols. Figure 1 shows an external picture of the prototype as well as an internal picture of the cell showing the multiple beams of a 532-nm laser been reflected in the cell mirrors. The beams showed in the internal picture reflect the real scattering of the laser photons by the aerosol particles inside the cell.

As a byproduct of the multiple reflection cell, using the same electronics, we have also built a single path laser extinction cell to measure of smoke aerosols generated in the United States Forest Service Fire Facility (USFS-FF). The single-path extinction cell was used in combination with several other aerosol, gas, and radiative instrumentation in a joint experiment coordinated by the USFS. During this experiment, different vegetation was burned to study aerosol and gas emission by biomass burning and its correlation with (remote sensing of) fire radiative energy. Figure 2 shows of the results correlating the fire radiative energy (W/m2) with the aerosol scattering and extinction coefficients. The aerosol scattering coefficient was measured with a commercial integrating nephelometer and the extinction coefficient was measured with the single path extinction cell built as part of this effort. The high correlation between the extinction and scattering coefficients show the quality of both measurements and the different behavior with regard to the fire radiative energy indicates the complexity of the physical processes correlating the vegetation fire and the aerosol emission. In the first stage of the fire, indicate by the rise of the fire radiative energy there is almost no emission of aerosols. As the fire evolves to its maximum intensity and subsequent smoldering phase, there is a sharp increase in particle emission and a sharp emission minimum in the flaming-smoldering transition. This data still need to be analyzed in more detail, combining the other parallel measurements performed during the experiment.

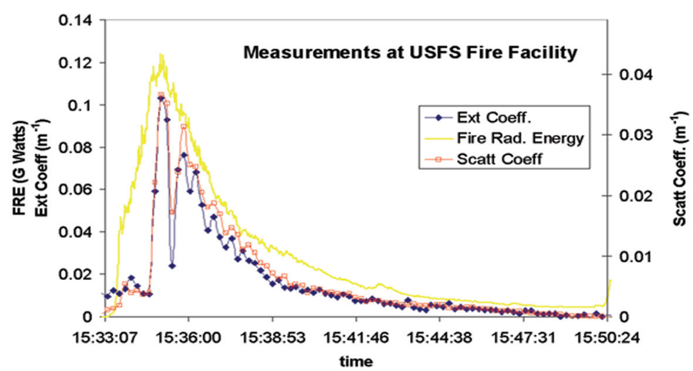


Figure 2. Application of the single path extinction cell in the United States Forest Service Fire Facility in Montana, showing the correlation between extinction and scattering coefficients by the emitted aerosols versus the fire radiative energy.

Another result obtained as part of this effort was the measurement of aerosol spectral absorption properties in a wide spectral range not currently available in the literature. Figure 3 shows a comparison between the aerosol absorption efficiency measured in Sao Paulo, Brazil, versus the Wallops area in Virginia. There are several important features that can be observed in this figure. The absorption efficiency of the aerosol from Sao Paulo is ten times stronger than the absorption efficiency of the Wallops area aerosols. The spectral behavior of the aerosol absorption generally followed the 1/wavelength curve indicated by the thin blue line over the Sao Paulo measurements, except for the UV, where the absorption efficiency is stronger than the expected absorption by black carbon. This behavior probably indicates extra absorption caused by organic aerosols and usually is not included in the aerosol absorption models. Other important results not shown here indicate the combination of small black carbon and large dust particles producing very particular spectral dependence behavior.

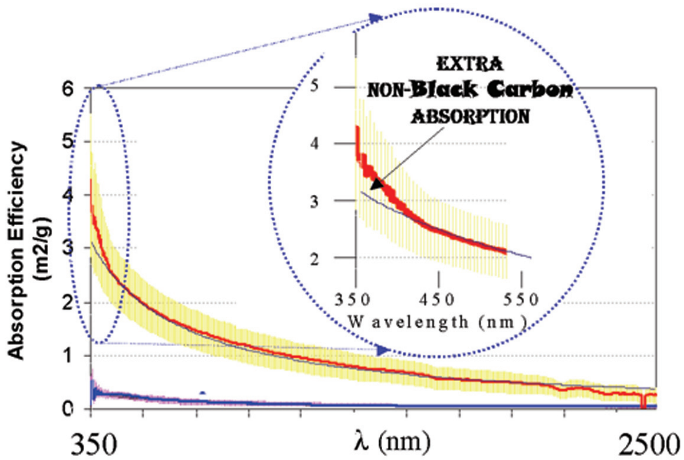


Figure 3. Results of the spectral aerosol absorption efficiency measurements comparing aerosol properties from Sao Paulo, Brazil, and from Virginia. Results covering this spectral range are usually not available in the literature. Absorption efficiency is measured in meters-squared per gram.

The main applications were the use of the single-path extinction cell in collaboration with the United States Forest Service for the measurement of smoke aerosol emissions and its correlation with the fire radiative energy, and the measurement of aerosol absorption spectral properties improving microphysical aerosol models in general. He made many presentations of the data, including:

* Martins, J. V.; Spectral absorption measurements of Black Carbon and other aerosols, presented in the workshop "History of Carbonaceous Aerosols in the Industrial Era", 24-25 Nov, 2003, NASA GISS, New York.

* Martins, J. V.; Artaxo, P.; Kaufman, Y., In situ and Remote Sensing Characterization of Spectral Absorption by Black Carbon and other Aerosols, Joint Assembly of the European Geophysical Union, American Geophysical Union, and European Union of Geosciences May 2003, Nice, France

* Martins J. V., Black carbon and aerosol absorption via in situ and remote sensing, Invited Lecture presented at the Update on Aerosol Research in NASA Goddard – Workshop, Greenbelt, MD, October, 2003.

* Martins, J. V., MODIS Aerosol Team, Progress and Directions for the CLAMS Experiment data analysis, presented in the CLAMS workshop, Greenbelt, MD, February 2002.

* Martins J. V., L. Remer, A. Castanho, Y. Kaufman, P. Artaxo, S. Mattoo, R. Levy, R. G. Kleidman, P. V. Hobbs, A. Plana-Fattori, M. Yamasoe, J. Redemann, Aerosol characteristics during the CLAMS experiment: in situ and Remote Sensing Measurements, presented in the American Geophysical Union Spring Meeting, 28-31 May 2002, Washington, D.C.

* Martins J. V., Measurements of Aerosol absorption over sunglint: on-going science work, Invited Lecture presented in the Aerosat pre-Science Team Meeting, Greenbelt MD, March, 2002.

* Martins J. V., Aerosat, black carbon and aerosol absorption, Invited Lecture presented at the Review of the Aerosol Research in Goddard – Workshop, Greenbelt, MD, October 2002.

Planned Future Work:

We plan to develop and improve algorithms for the measurement of aerosol absorption over the ocean from space; apply the multiple-reflection cell prototype in the measurement of aerosol and absorption properties of several aerosol types; and use the spectral absorption measurements in large scale for the measurement of aerosol absorption properties in a wider spectral range than usually available in the literature.

Summary:

Our works both utilizes and further develops the multiple reflection cell prototype, designed by one of us (Vanderlei Martins) under a FY 2002 DDF. This prototype won the Goddard Innovative Instrument Development award in 2003. The multiple reflection cell prototype is an instrument to measure aerosol absorption. We used the cell -- a box with instruments about a meter long and a half meter wide and high -- to better characterize black carbon and other aerosol absorption properties. Results from this work are used in the development of the Glory satellite mission, planned for launch in 2006, and in the development of new concepts for the measurement of aerosol properties from space. Goddard can also benefit from these results by successfully proposing innovative techniques to measure aerosol properties from ground and space, as well as better addressing the aerosol impact on climate. Several new aerosol initiatives are underway and should benefit from these results. We have obtained enough knowledge from this project to pursue development of algorithms for aerosol absorption over the ocean sunglint; we have extended knowledge of aerosol spectral absorption properties; and we have successfully applied the part of developed instrumentation that measures properties of smoke aerosols. These achievements reflect the success of the project. Accurate characterization of aerosol scattering properties from space was a major risk factor in retrieving aerosol absorption properties via remote sensing, but this level of accuracy proved possible through the use of spectral, multi-angle polarization measurements.

In-Situ Combination of Magnetic and Satellite Image Data

Principle Investigator: Compton J. Tucker (code 923) and Peter J. Wasilewski (691)

Other Investigators: Brian Rose (Department of Classics, University of Cincinnati)

Initiation Year: FY 2003

Funding Authorized for FY 2003: $10,600

Actual or Expected Expenditure of FY 2003 Funding: $10,600

Status of Investigation at End of FY 2003: Completed

Expected Completion Date: Completed

Purpose of Investigation:

We proposed to combine magnetic data and high-resolution satellite data to assist in archaeological investigations. Magnetic data contains information about the contents of soil that might point to traces of earlier civilization. This would include, for example, the presence of iron or the remains of manmade structures of limestone or granite. High-resolution satellite imagery data provides a means for highly controlled mapping to understand features across a wide region, including mounds or faint traces of old roads. To undertake the investigation, we purchased a linux workstation and associated software; installed image analysis software such as ArcInfo; and modified our existing magnetic analysis software to handle the magnetic signals we were to record, and then overlaid these onto existing panchromatic satellite imagery, such as 1-meter Ikonos images, 10-meter Earth Observer-1 images, 15-meter Landsat-7 images. All of this was bundled into a workstation that could be taken into the field with the magnetometer for field surveys. It was our intention to analyze our ground-collected magnetic data, and aircraft drone magnetic data if acquired, within a few minutes after data collection. This would enable additional magnetic surveys to be made immediately or the next day in specific areas where unusual features are revealed (figure 1). Combining the magnetic and satellite data provides a much better geospatial context for understanding the magnetometer data.

Accomplishments to Date:

Figure 1 illustrates what we will further investigate with our DDF-funded system. This figure was acquired in 2002 at the site of Troy in northwestern Turkey. We acquired the workstation hardware, software, and were ready to perform an "in the field" test combining ground-collected magnetic data and satellite data. Unfortunately, the Iraq war of 2003 precluded our testing of the hardware and software in the field in Turkey. We hope to test the hardware and software in Turkey in the summer of 2004 in the area of Granicus to the south of the Sea of Marmara, in northwestern Turkey. We are scheduled to be working in this area where Alexander the Great defeated the Persians in 334 B.C. at the battle of Granicus. We also purchased a Quickbird satellite image of the area from digital globe and are waiting to see if the archaeological permit submitted by Brian Rose to the Government of Turkey for excavation in the Granicus area will be granted for the summer of 2004.

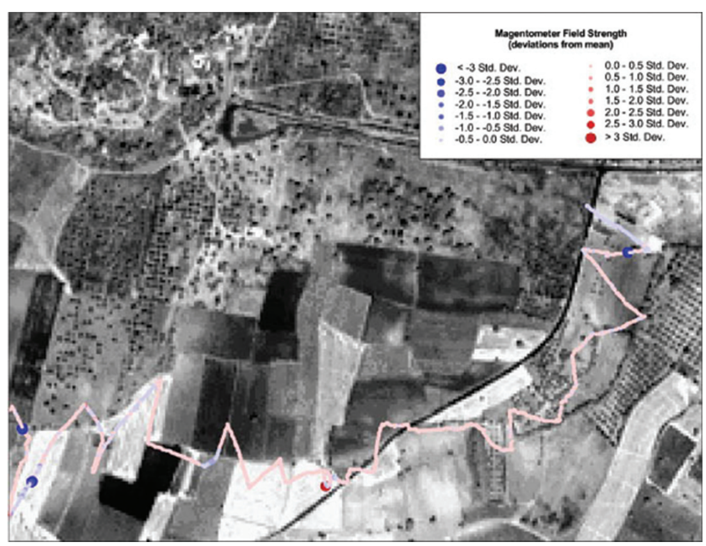


Figure 1. An example of how we propose to combine magnetic data and high-resolution satellite data to assist in archaeological investigations. This figure is from an aqueduct survey we performed at Troy during the summer of 2002.

Planned Future Work:

We are ready to begin work in the field in July-August 2004 with the hardware, software, and satellite data we acquired in FY2003.

Summary:

We are now ready to analyze magnetic and satellite data in the field from archaeological sites. NASA and Goddard would benefit from media exposure generated by our contribution to preserving cultural history. Our criterion of success is rapid data analyses in the field of magnetic and satellite data. The Iraq conflict of 2003 prevented and detained work in Turkey because of unrest and anti-American feelings. We hope to do better for 2004.

Investigation of Bose-Einstein Condensates for Advanced Gravity Gradiometer Designs

Principal Investigator: Dave Skillman (Code 924)

Co-Investigators: none

Initiation Year: 2003

FY 2003 Authorized Funding: $47,000

Actual or Expected Expenditure of FY 2003 Funding: $40,000 for Welch Mechanical Designs, LLC; $7,000 in-house

Status of Investigation at End of FY 2003: To be continued in FY 2004 with funds remaining from FY 2003

Expected Completion Date: June 2004

Purpose of Investigation:

There are several purposes of this investigation: to analyze the potential performance of new, in-house gravity gradiometer designs via computer simulations; to identify geophysical phenomena that would become observable with the dramatically increased sensitivity of cold-atom interferometer designs; to use these studies to seed new instrument/mission proposals; and to identify key technology elements needed to establish a starting point for Goddard research into these condensates. Mapping the gravitational fields of planets, including the Earth, can reveal insight into their structure. The Earth's gravitational field is not uniform but lumpy, varying across water and different terrains. The Hawaiian Islands, for example, represent a bump in the gravitational field, as do land movements caused by earthquakes and the redistribution of atmospheric mass as it changes from season to season. Sensitive measurements of minute changes in the gravitational field essentially enable us to peer into the Earth to see deep ocean currents, ground-water storage, or any flow or exchange of mass from one region to another. The technology to measure such changes currently employs radio waves and laser photons. The atoms that make up matter are more sensitive to gravity than the photons of light. Bose-Einstein condensates are a newly confirmed state of matter (different from solid, liquid and gas), and these cold, slow-moving atoms can act like a laser to measure gravitation fields.

Our goal is to investigate the design of spaceflight versions of the existing laboratory subsystem elements involving Bose-Einstein condensates, namely: atomic vapor ovens (which liberate individual atoms from metals), magneto-optical traps (which slow the atoms to about a millimeter per second and enable them to form a Bose-Einstein condensate), and evanescent-wave atom mirrors (which can be used to create an interferometer from the slow moving atoms). Similar to the way that changes in arm lengths can cause changes in phase in two laser beams, gravity can change the speed of atoms in the interferometer, which changes their phase.

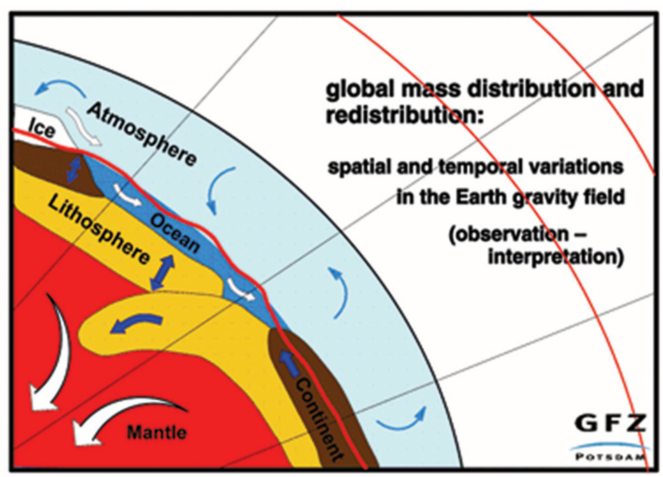


Figure 1. Long-term observations of the Earth's gravity field permit monitoring of processes on, above and inside the Earth's surface.

Accomplishments to Date:

I have prepared a paper to the Journal of Geophysical Research. This paper is the first in a series and calls out the broad capabilities of a satellite-based cold-atom gravity gradiometer along with a feasibility estimate of building such a device. A first-cut analysis of the expected sensitivity has been developed and shows sensitivity improvements over currently extant technologies.

Planned Future Work:

More detailed performance simulations will be developed followed by a design and evaluation of the mechanical details for a satellite instrument.

Summary:

This DDF applies a new technology (Bose-Einstein condensates) to the long-standing problem of determining the gravitational field of the Earth and other bodies in the Solar System. If this instrument turns out to be feasible, major improvements in measuring gravity fields will be possible. The DDF will be successful if it can lead to the development of a new spaceflight Earth-observing instrument. Risk elements are related to the mathematical decoupling of the various noise accelerations that such an instrument might detect. The sensitivity may turn out to be overwhelmed by the environmental noise.

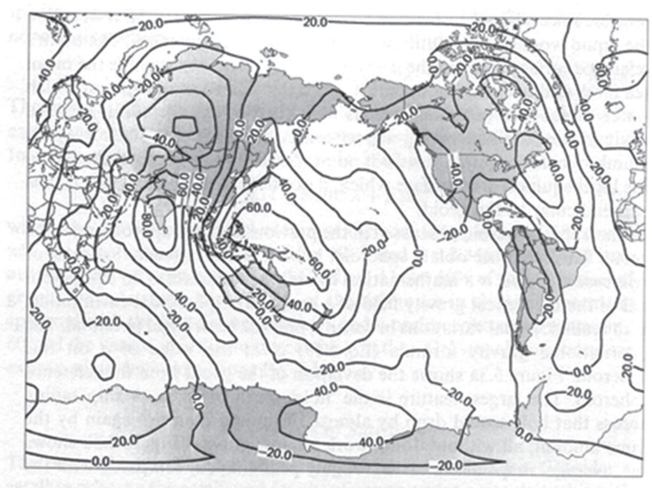


Figure 2. The Earth has a complex gravity field, which changes as mass is redistributed around the surface. Monitoring the gravity field permits tracking the movement of the atmosphere, oceans, and land (earthquakes, glacial rebound).

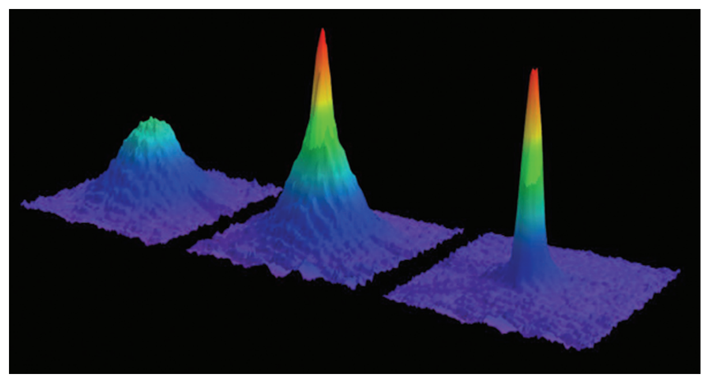


Figure 3. Growth of the Bose-Einstein Condensate as cooling progresses (2-D velocity/density plot at three successive times). Credit: Cold Atom Group at MIT.

Optical Measurements of Particulate Organic Carbon in the Sea

Principal Investigator: Michael J. Behrenfeld (Code 970)

Co-Investigators: Wayne Wright (972), Frank Hoge (972), Viktor Feygels (EG&G)

Initiation Year: 2003

FY 2003 Authorized Funding: $65,500

Actual or Expected Expenditure of FY 2003 Funding: Lunchbox computer, $3,500; Lidar hardware, $31,500; machining, $10,000; contract with Viktor Feygels, $25,000

Status of Investigation at End of FY 2003: To be continued in FY 2004 with funds additional FY 2004 DDF funding of $32,500

Expected Completion Date: December 2004

Purpose of Investigation:

Field measurements have repeatedly shown that the concentration of particles in the water can be assessed from changes in light scattering, and that this information can be directly interpreted to reveal the amount of "living" carbon in a given ecosystem, such as that from vegetation. While never demonstrated, an opportunity clearly exists for studying and monitoring ocean carbon pools from space if a technique can be developed that measures ocean light scattering from above the atmosphere. The overarching objective of this study, therefore, is to develop such a system for assessing the concentration of carbon particles in the ocean. The basic approach we've adopted for this project is to use a lidar system (a laser light source combined with a receiving telescope) that measures light scattering over a range of different fields of view (FOV), which will be varied by a computer-controlled, mechanical iris within the light path of the lidar's telescope. The underlying principle is that, as the telescope FOV increases from very narrow to very wide, the light collected changes from being dominated by photons scattered only once by an in-water particle to photons experiencing multiple scattering events in the water before returning to the telescope. This permits calculations of the beam attenuation in the water, which is directly proportional to the number of particles.

Accomplishments to Date:

Based on optical theory, Howard Gordon at the University of Miami described how the light attenuation coefficient measured with an ocean lidar might be expected to change over various FOVs as particle concentrations and sizes varied (with attenuation increasing with increasing concentration) (figure 1). According to this theory, the lidar we are constructing will measure light attenuation at 5 to 20 different FOVs and, by fitting a curved line to the resulting data, permit an estimation of the attenuation coefficient that would be observed if a FOV = 0 if such a measurement could be made. (It can't because at FOV = 0, no light would be collected by the telescope). This attenuation coefficient at FOV = 0 is equivalent to the scattering measurements measured in the field that are so well related to the concentration of living carbon particles.

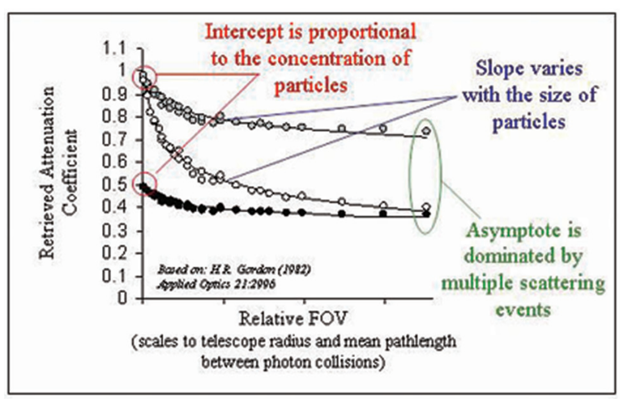


Figure 1. Theoretical basis of our lidar system development. In this figure, light attenuation is measured for three different particle populations. The solid black symbols represent a region with low concentrations of particles that are relatively small. The gray symbols represent a population with approximately twice as many particles as the solid black symbols, but of the same size. The open symbols would correspond to a population of larger particles, but of the same concentration as the gray symbols.

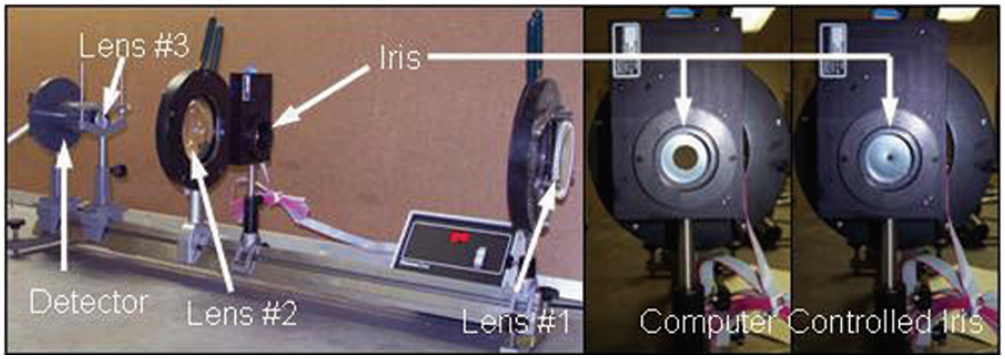


Figure 2. Initial setup and testing of the telescope components for the particulate carbon lidar showing the three central lenses, specialized photomultiplier (PMT) detector, and the computer controlled iris for achieving measurements of scattering at variable FOVs.

Our efforts were initiated by Viktor Feygels, who conducted additional theoretical analyses of the fundamental optical principles originally outlined by Gordon in 1982. Based on these studies, a final design for the lidar's telescope was completed and construction initiated. The central components were first assembled and tested on an optical bench at the NASA Wallops Flight Facility (figure 2).

Following these initial tests, the telescope casement was machined, the laser light source (532 nm) was acquired and integrated into the system, and computer hardware and software purchased and developed. In late October of 2003, the fully assembled lidar was successfully tested using 2 targets at different distances and at different angles (figure 3).

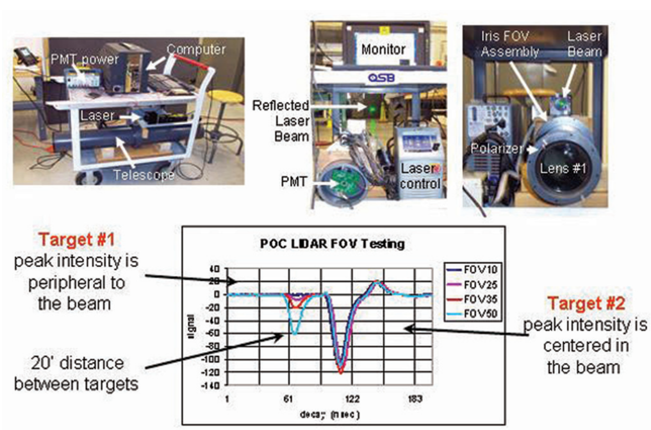


Figure 3. Initial setup and testing of the telescope components for the particulate carbon lidar

Planned Future Work:

The newly constructed particulate organic carbon lidar is currently scheduled for testing in experimental optics tanks in January and February of 2004. After these system characterizations and calibrations, the lidar will be taken to sea for initial field validations. Later in 2004, modifications are being considered for system/measurement testing from an airplane. All of these tank, field, and airborne tests are aimed at ultimately supporting satellite remote sensing measurements of ocean particulate carbon concentrations, which will lead us to a better understandingof life on our home planet and better enable us to monitor and protect our precious ocean resources.

Summary:

Our project's innovative feature is the optical retrieval of underwater waveforms at multiple telescope fields of view. For Goddard, this provides fundamental ground and airborne validation measurements for a future remote sensing mission. Our criterion for success is optically retrieving estimates of particulate organic carbon concentrations that agree with in-water measurements. In regards to technical risk, in-water testing of the lidar has not yet been conducted, so the most challenging aspect of this project is still ahead: specifically, using retrieved optical data to estimate particulate carbon concentrations.

Optical Properties of Black Carbon and Terrigenous Chromophoric Dissolved Organic Matter in the Coastal Ocean

Principal Investigator: Antonio Mannino (Code 971)

Co-Investigators: none

Initiation Year: 2003

FY 2003 Authorized Funding: $71,000

Actual or Expected Expenditure of FY 2003 Funding: Agilent Technologies, $57,300; Dell, $2,100; Government Scientific Source, $2,400; Millipore Corp., $2,200; Phenomenex, $1,400; Savillex Corp., $1,300; other vendors of laboratory supplies, $4,300.

Status of Investigation at End of FY 2003: To be continued in FY 2004 with funds remaining from FY 2003, possibly with additional FY 2004 DDF funding

Expected Completion Date: Fall 2004

Purpose of Investigation:

The goal of the project is to examine the optical properties and composition of black carbon and terrigenous (derived from land plants) dissolved organic carbon in coastal waters. The ultimate objectives are to enhance our understanding of the carbon cycle and to improve NASA's remote sensing capabilities for ocean color data products in coastal waters. Dissolved organic matter (DOM) in the ocean constitutes one of the largest pools of organic carbon in the biosphere (similar to the amount of carbon in the atmosphere as carbon dioxide), yet much of its composition remains uncharacterized. Black carbon (BC), an inert and chemically heterogeneous carbon component, is produced by incomplete combustion during forest fires, other biomass burning, and fossil fuel combustion. Observations of black carbon particles (soot and charred biomass) in the atmosphere, ice, rivers, soils and marine sediments suggest that this material is ubiquitous in the environment and must be present in the ocean's DOM. Because of its inertness, BC could be an important long-term sink for carbon in the ocean. The relevance of the work to the carbon cycle is that we have limited information on the flux of BC and terrigenous DOM from land to the ocean. If we can somehow measure this flux from space throughout the globe then we would have a better understanding of the carbon cycle and whether natural climate variability and/or anthropogenic activity influence these fluxes.

Accomplishments to Date:

My previous work in Delaware Bay demonstrated the presence of colloidal BC (nominal size of 1 nanometer to 0.2 microns; 9±6.5% of dissolved organic carbon DOC) in the estuary and adjacent ocean, revealing the significance of land-margin contributions of BC to the coastal ocean (Mannino & Harvey, in press). Mechanisms that can introduce BC to the ocean include atmospheric deposition of land-derived BC aerosols, river-estuary transported material and marine diesel engine exhaust. In fact, satellite images have demonstrated that aerosols originating from vegetation burns in Africa are transported across the Atlantic Ocean. At present, there is no information on the optical characteristics of BC in coastal and open ocean waters. Black carbon aerosols have a strong capacity to absorb and scatter light (albedo of 0.5). Discharge of terrigenous DOC and sediments into coastal waters by rivers and extensive phytoplankton blooms in coastal ocean waters yield variable concentrations and composition of chromophoric DOM (CDOM; the optically active fraction of DOM) and particles. This complicates the bio-optical properties of the coastal ocean due to the strong absorptive character of terrigenous CDOM and phytoplankton and impedes accurate satellite-based measurements of ocean color constituents. The presence and absorptive characteristics of particulate and dissolved/colloidal BC in the coastal ocean could also influence the remote sensing of chlorophyll and CDOM.

Initial efforts of this DDF have focused on developing new analytical procedures to isolate and optically characterize black carbon and terrigenous dissolved organic matter. DDF funds became available in April 2003 and the high-performance liquid chromatograph instrument, filtration equipment and supplies essential to proceed with the research were in

Figure 1. Large volume water samples were collected from shore near the Susquehanna River mouth (Havre de Grace, MD) on June 12, 2003 and the Patuxent Estuary (Solomons Island, MD) on June 30, 2003. Additional samples were collected aboard the R/V Cape Henlopen along transects from the Delaware River to the coastal ocean beyond the continental shelf break in November 2002 and July 2003. 1 - Susquehanna River, 2 - Patuxent Estuary, 3 - Delaware Bay and coastal ocean.

place at Goddard in late May 2003. Large volume samples were collected from the Susquehanna River and Patuxent Estuary in June 2003 for methods development (figure 1). Seawater samples were collected from coastal ocean sites on cruises of opportunity in November 2002 and July 2003 (Delaware Estuary and Atlantic Ocean).

To isolate and concentrate BC and terrigenous DOC, filtered seawater is pumped through solid phase extraction (SPE) cartridges containing either C-18 bonded silica or Phenyl bonded silica (figure 2). Two SPE matrices were tested to determine which material efficiently isolated DOC and BC. The thermal oxidation technique is used to remove non-black carbon material. Sub-samples of DOM isolated on SPE cartridges are thermally oxidized at 375°C for 24 hours within a muffle furnace. Carbon content of both thermally oxidized (BC) and non-thermally oxidized samples (isolated DOC) is measured using a CHN elemental analyzer. The DOM isolated on the SPE cartridges is analyzed by reverse-phase high performance liquid chromatography (HPLC) in order to separate BC and terrigenous

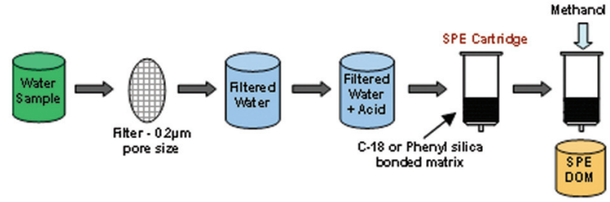


Figure 2. Filtration and isolation of dissolved organic matter (DOM) from river, estuarine and ocean samples. To isolate, concentrate and desalt DOM from filtered water samples, the filtered water is acidified and pumped through SPE cartridges containing either C-18 bonded silica or Phenyl bonded silica. The DOM of interest, including BC and other terrigenous DOM, adsorbs to the C-18 or phenyl silica matrix. The isolated DOM is desalted with ultrapure water and desorbed from the cartridge with methanol.

DOM from other matter and measure their absorbance and fluorescence spectra.

With the help of a summer student, Chris Bareither (Summer Intern Program), we determined that the C-18 SPE cartridges isolated a greater proportion of dissolved organic carbon (DOC) than the Phenyl SPE cartridges (figure 3a). Furthermore, the C-18 SPE cartridges isolated more BC from the Patuxent sample than the Phenyl SPE (figure 3b). The low BC content in the Susquehanna River sample is likely due to dilution of BC from the high precipitation and river discharge in 2003. HPLC analysis of the Susquehanna River sample demonstrates similar fluorescence spectra for both types of SPE cartridges (figure 4). However, the fluorescence emission response at 440nm (typical of CDOM) is more intense for the C-18 SPE cartridge. The absorption spectra from HPLC analysis are typical of coastal DOM (not shown). Current research is focusing on HPLC analysis of the urban dust aerosol standard (from NIST) and samples collected in Delaware Bay-Atlantic Ocean and also the Patuxent Estuary, which contain higher amounts of BC than the Susquehanna River sample.

Exponential decay curves for CDOM absorbance from ultraviolet through the red region of the visible spectrum are typical of natural waters (figure 5). Samples collected from rivers, near the urban region of Philadelphia (DB12) and the Delaware Memorial Bridge (DB16) show the highest absorption coefficients. Coastal ocean and offshore samples demonstrate the lowest absorption coefficients. Higher CDOM absorption was observed in the Delaware River and upper bay in November 2002 than July 2003, indicating both higher DOC concentrations and terrigenous components upstream in November. However, for the lower bay (DB 22-26), CDOM absorption was higher in July, due to the downstream flux of terrigenous DOM to the lower bay from the

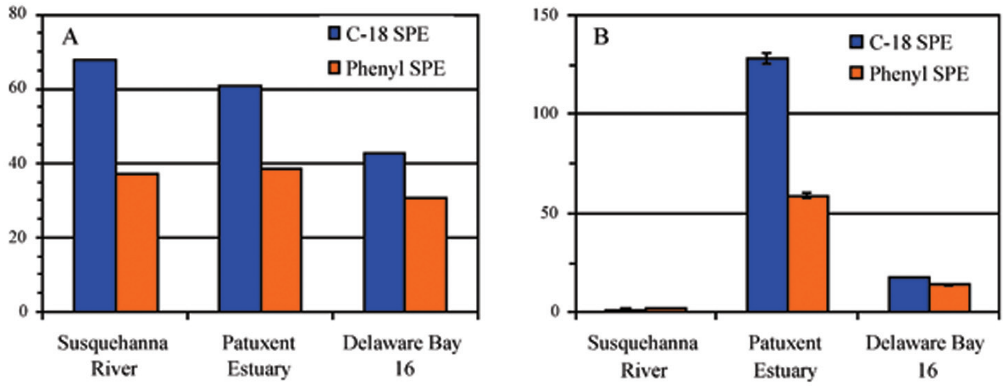


Figure 3. Isolation of (a) dissolved organic carbon (DOC) and (b) black carbon by the C-18 and Phenyl solid-phase extraction cartridges for the Susquehanna River, Patuxent Estuary and Delaware Bay station 16 (DB16; near the Delaware Memorial Bridge).

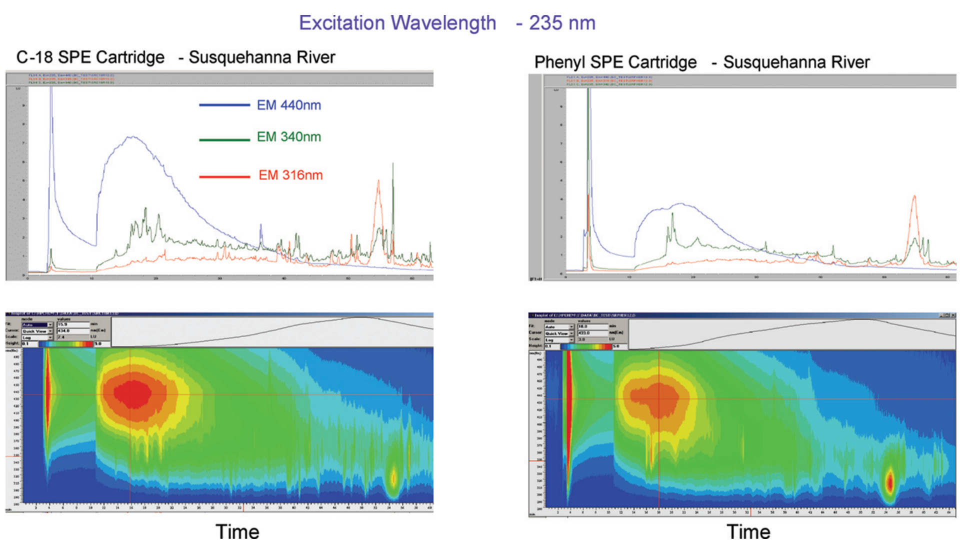


Figure 4. Fluorescence spectra from HPLC analysis of Susquehanna River DOM isolated on C-18 SPE and Phenyl SPE cartridges at the excitation maximum of 235nm and multiple emission wavelengths (EM). Time is in minutes.

higher freshwater discharge in 2003. The strong correlation of DOC and the absorption coefficients at 355nm [a(355)] and 412nm [a(412)] for the November 2002 and July 2003 Delaware Bay-Atlantic Ocean samples and for a(412) only in July (figure 6) suggest that ocean color satellite retrieval of DOC is possible using field-validated measurements and a satellite ocean color band in the near ultraviolet (e.g. 355nm). Further work is needed to determine whether an algorithm based on the 412nm band on MODIS (Moderate Resolution Imaging Spectroradiometer) can be utilized to retrieve DOC. Climatic variability, drought conditions in November 2002 and high precipitation in 2003, appears to impact the DOC-CDOM relationship in coastal waters.

Planned Future Work:

Research will continue on methods development to optically characterize and quantify black carbon and terrigenous DOM in river, estuarine and coastal ocean samples collected in 2002 and 2003. HPLC analyses of DOC isolated from seawater will continue with emphasis on separating BC and terrigenous DOM from other organic compounds. Lignin compounds, indicative of terrestrial plants, will be measured from DOM isolated on SPE cartridges to quantify the terrigenous component of DOC. Additional seawater samples from the eastern equatorial Pacific Ocean (collected Nov. 2003 by Behrenfeld and Worthington) and from across the

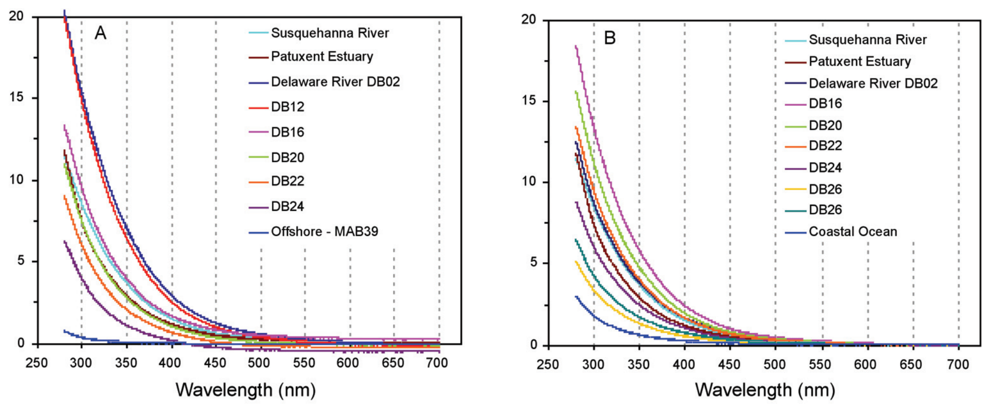


Figure 5. CDOM absorption coefficient curves for the Susquehanna River, Patuxent Estuary and the Delaware Bay-coastal ocean samples from (a) November 2002 and (b) July 2003.

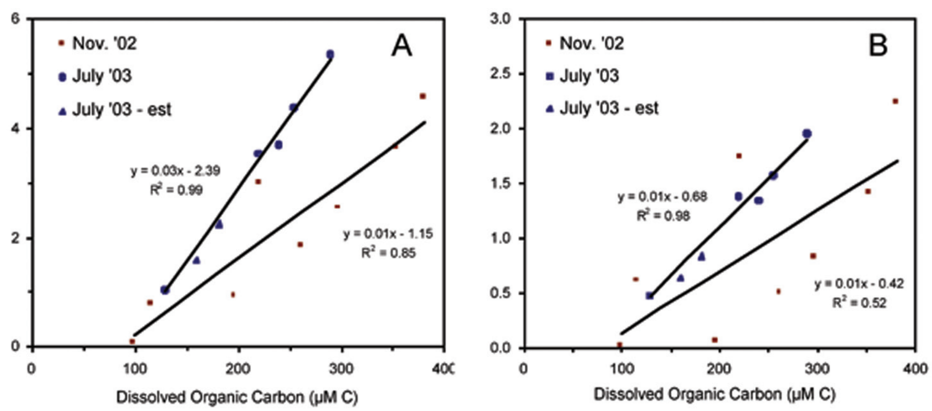


Figure 6. Dissolved Organic Carbon versus CDOM absorption coefficients at 355nm and 412nm for the (a) November 2002 and (b) July 2003 Delaware Estuary field campaigns. Data extends from DB16 to the coastal ocean.

Atlantic Ocean (collection in March 2004 by the PI from the Caribbean to Africa) will also be examined. Because of the extensive biomass burning, Africa and the Amazon basin are likely significant sources of BC to the Atlantic Ocean.

Summary:

Little is known of the flow of black carbon (that is, material derived from combustion of fossil fuels and biomass) and dissolved organic matter from land plants transported from the land into the ocean. If we could measure these fluxes from space, we could have a better understanding of the carbon cycle and whether natural climate variability or anthropogenic activity influence these fluxes. Our research activity is unique in that it will supply the first results on the optical character of black carbon from the ocean. Moreover, our results suggest that it is possible to use field-validated measurements and satellite-based data to study the contribution of dissolved organic carbon in coastal waters. The study enhances our understanding of the carbon cycle and can improve Goddard and NASA's remote sensing capabilities for ocean color data products in the coastal ocean. Our success criteria are (1) successful laboratory measurements of the different ocean carbon constituents in our water samples, and (2) successfully distinguishing the various components optically. The technical risk is that distinguishing components optically might not be possible. For example, two components with different environmental effects might have similar optical properties.

Chris Bareither (funded by the Summer Intern Program) assisted with sample collection and analysis. I thank the captain and crew of the R/V Cape Henlopen and Drs. David Kirchman and Matthew Cottrell (University of Delaware) for their invitation to participate on the Delaware Bay cruises. I am also grateful to Mike Behrenfeld (972) for the use of equipment in his laboratory and Kirby Worthington and Don Shea for assistance with the CHN elemental analyzer.

Global Carbon Cycle: Development of a Bicarbonate Ion Lidar

Principal Investigator: Frank Hoge (Code 972)

Co-Investigators: James Yungel (EG&G), Viktor Feygels (EG&G)

Initiation Year: 2002

Aggregate Amount of Funding Authorized in Earlier Years: $76,000

FY 2003 Authorized Funding: $52,000

Actual or Expected Expenditure of FY 2003 Funding: EG&G, $46,000; CVI Laser Inc., $6,000

Status of Investigation at End of FY 2003: To be continued in FY 2004 with funds requested from NASA Headquarters

Expected Completion Date: December 2003 (initial DDF portion)

Purpose of Investigation:

A major question in science concerns the ocean's capacity to absorb atmospheric carbon, which in the form of carbon dioxide can lead to global warming. Over the past two centuries, atmospheric carbon levels have risen from about 240 ppm to 360 ppm. Understanding future levels depends on knowing more about the carbon cycle between air and water. The goal of this investigation is to determine the feasibility of airborne, remote laser-induced measurement of carbonate concentrations in seawater. Carbonate refers to inorganic carbon, which makes up about 97% of the carbon in the ocean. Current techniques measure organic carbon (locked up in chlorophyll), which makes up only about 3% of the oceans carbon. Present wet-chemistry laboratory measurements of inorganic carbon -- for example, on a boat -- is inefficient and not extendable to remote sensing. We propose using lasers that will cause the inorganic carbon molecules to vibrate and to emit radiation at a highly specific color (Raman effect) for relatively easier measurement. These molecular emissions are very weak and initial experiments seek to first accomplish the task from airplane altitudes.

Accomplishments to Date:

Previous years DDF efforts borrowed heavily on use of existing RTOP funded laser-induced fluorescence spectrometers (the NASA Shipboard Laser Fluorometer). These efforts have produced promising laboratory results for saturated carbonate concentrations, and for dilutions down to concentrations approximately 100 times greater than seawater levels. Present year research comparing Raman spectra of seawater shows the detection of the sulfate ion Raman signal, confirmed by comparison to sulfuric acid solution (figure 1). The shape of the sulfate ion Raman peak suggests a possible "shoulder" in the region of the carbonate ion Raman region (assuming somewhat similar Raman induction between carbonate and sulfate ions, the seawater concentration of the carbonate ion is approximately 5% of the sulfate ion hence the spectral location and amplitude of this shoulder is quite believable). However the laboratory effort revealed that the high scatter and low resolution of our single-grating spectrometer doesn't allow full resolution of the carbonate peak. Additional 2003 DDF efforts centered upon using an improved double-grating spectrometer, but its acquisition was delayed by unexpected procurement freezes. The double-grating spectrometer should eventually allow improved spectral resolution and reduced scattering that will enable detection of the carbonate signal to levels approaching carbonate concentration in natural seawater.

Additional present-year DDF research using a gated image-intensified CCD array as a detector on the Airborne Oceanographic Lidar (AOL) has demonstrated the potential for transferring the laboratory results into the remote sensing arena. Airborne laser spectra (figure 2) from initial engineering flights in the western Atlantic Ocean show the potential for extending the above laboratory results to airborne platforms. The airborne results shown in figure 2 are the first complete high-resolution emission spectra recorded by the GSFC AOL instrument. The 532 nm laser induced emission spectra shows the major water O-H stretch Raman at about 645 nm and the chlorophyll fluorescence peak at about 683 nm. The region between 560 and 590 nm where the ionic sulfate and carbonate Raman peaks should occur demonstrates that the required resolution is available and that detection should be possible when sufficient laser power is eventually used. This is a significant milestone in assessing extension of the laboratory results to future remote-sensing applications. A future milestone of the airborne effort is to detect the 583-nm bending mode water Raman since it will establish a new level of sensitivity and resolution for airborne oceanic lidars that is suitable for carbonate ion Raman detection.

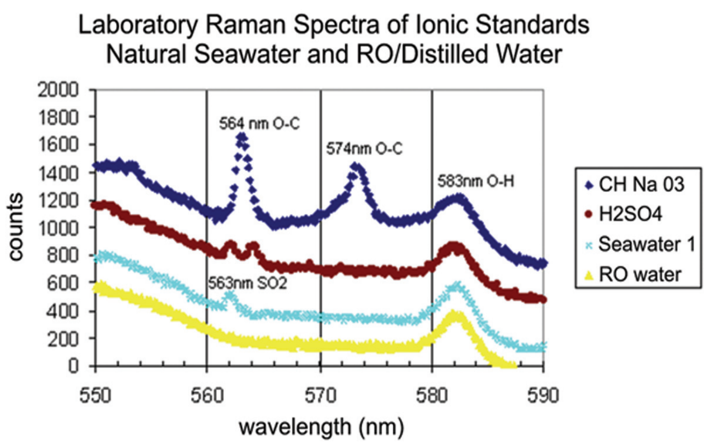


Figure 1. Laboratory 532-nm laser-induced Raman spectra of seawater and carbonate and sulfate ionic standards. Note the detection of the sulfate ion in seawater and possible carbonate Raman shoulder on the red side of the sulfate peak. Also note the unwanted scatter of laser radiation within the 550 to 560 nm region. RO is pure water obtained by reverse osmosis. The bending mode water Raman at 583nm can be used as a measurement standard.

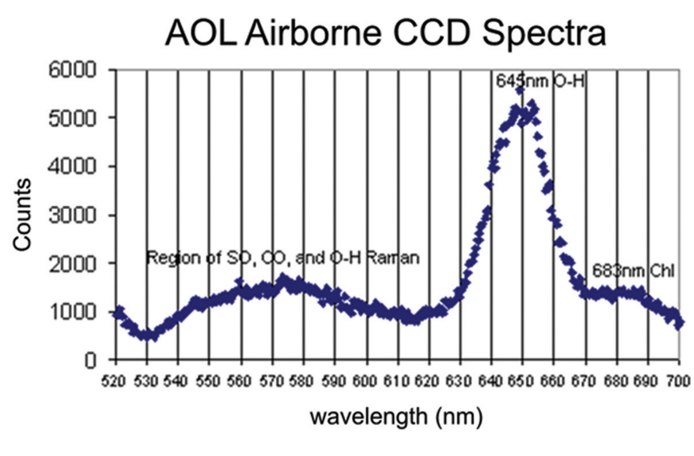


Figure 2. Airborne 532 nm laser induced Raman spectra of seawater. This is the first use of a high resolution gated CCD detector to capture complete laser-induced emission spectra.

Planned Future Work:

Based upon the DDF results, new funding sources will be sought to allow laboratory work to continue by using the improved double-grating spectrometer (following delayed procurement) to determine if the carbonate Raman peak can be resolved in natural seawater samples. If this step is successful, a shipboard laser-induced carbonate Raman sensor will be developed for eventual testing by the ocean research community. Improvements (increased laser power and optical improvements) in the Airborne Oceanographic Lidar may result in advancement of the laboratory work into the airborne remote sensing realm.

Summary:

The project is innovative in that no remote-sensing method presently exists to detect the major carbon portions in the ocean: the inorganic carbon. Also, conventional shipboard methods are wet-chemistry and are not extendible to remote methods. The payoff to NASA if this method is eventually successful is that the airborne lidar methods may develop into passive satellite measurement of inorganic carbon pool. The criterion for success was to detect the carbonate ion in natural seawater in laboratory experiments. This was not achieved. However, it was learned that: (1) a double monochromator is required to reduce scatter of the exciting laser radiation into the weaker Raman spectra; (2) the spectral region from 560-590 nm is available but must compete with phytoplankton phycoerythrin fluorescence, an undesirable finding; and (3) commercial detectors having adequate sensitivity resolution are now available as demonstrated by airborne lidar flights. The major factors that may prevent eventual success are oceanic constituent phytoplankton fluorescence emission that could overwhelm the carbonate Raman signal and the (known) weakness of the carbonate ion Raman signal. For shipboard instrumentation the phytoplankton can be removed by filtering or high-power radiation, leaving the possibility that a new shipboard instrument could result from this work and would be about 20-times faster than present laboratory wet-chemistry methods.

Miniaturized Eddy Correlation Instrument for Small Unmanned Aerial Vehicles

Principal Investigator: Paul Houser (Code 974), Geoff Bland (972)

Co-Investigators: Ted Miles (512), Gabe Ladd (Student Intern, Boston University)

Initiation Year: 2002

Aggregate Amount of Funding Authorized in Earlier Years: $30,000

FY 2003 Authorized Funding: $30,000

Actual or Expected Expenditure of FY 2003 Funding: Edutech, $20,000; equipment and supplies, $10,000

Status of Investigation at End of FY 2003: To be transitioned to other funding

Expected Completion Date: September 31, 2004

Purpose of Investigation:

The purpose of this project is to develop a new method for investigating transmission of carbon dioxide and water vapor through the air. Traditionally, measurement of these fluxes has been from stationary-tower-based systems. The development of an airborne method of measuring carbon dioxide and water vapor flux has the potential to revolutionize not only the way we measure but the way we think about and understand these two critical components of our atmosphere.

Background: Exchange of water, energy, carbon, and momentum between the land surface and the atmosphere has strong influence on variability in weather and climate. Unfortunately, we have very few tools to observe these exchanges, and therefore critical processes remain unresolved in earth system models. A standard method of measuring land-air water, carbon, energy, and momentum exchange is by eddy covariance. Very simple in concept, eddy correlation measures air motion and a quantity of interest, such as water vapor, at high temporal frequency (10Hz). If on average, rising air is rich in water vapor, while sinking air is depleted, the net result is an upward flow of water, or evaporation. Over the past decade, eddy covariance instruments have been developed in a research mode and have just recently become commercially available for tower-based observations. It is believed that the surface heterogeneity has significant influence on near-surface flux patterns that give rise to “preferential flowpaths” whose dynamics are not observable by fixed instruments. There have only been a few research efforts to deploy these instruments on aircraft to obtain transects of land-air fluxes.

Determinating fluxes by eddy covariance from moving platforms is complicated by the motion of the platform, which must be determined accurately at high frequency. Wind instruments will sense wind relative to their movement, so their motion must be accounted for to obtain the wind with respect to the surface. Thus both the motion and the orientation of the platform carrying the wind instruments must be measured at the same frequency as the relative wind. Sonic or even propeller anemometers are appropriate for low-speed vehicles such as trucks or ultralight airplanes. The Global Positioning System (GPS) can be exploited to measure the motion of the wind instruments using its high precision in differential mode directly in earth coordinates at up to 10 Hz. The required GPS hardware is small and inexpensive and draws little power. Airborne flux measurement has in the past required large aircraft to carry heavy, power-hungry computers and sensors. The complexity and cost of these systems limited them to very few (two groups worldwide) who could afford the expensive instruments and could dedicate a large aircraft to the task. Unfortunately, large aircraft also cause serious flow distortion and restrict measurements to altitudes that are often unacceptably high to represent exchange with the ground. Thus, it is desirable that observations be made near the ground, at heights that tend to be uncomfortable for most airplanes (below 100 meters).

Accomplishments to Date:

In the last year our group in conjunction with Wallops Flight Facility has designed two UAV systems capable of carrying out a miniaturized eddy correlation system, and we performed a proof of concept using a ground-based mobile test platform. Our primary goal of a fully operational small UAV Plane based system was never built because the DDF funding from last year was half of what we requested, and safety assurance issues were more complex then foreseen. Thus we were forced to compromise and build a blimp-based system that, while it is unmanned, must be either tethered or towed behind an electric cart. This is a compromise in that it is easily mobile but not remotely piloted or autonomous.

We have developed a suite of instruments that is light enough to be mounted on a small UAV. We have also developed a mobile ground based test bed (figure 1) and towed a mobile airborne system (figure 2). These two test beds are designed for initial testing so we may begin to validate the instruments. The airborne test platform will also help us to develop a method to correlate the position data for each measurement with the environmental data, so that the three dimensional motion's effect upon the data may be accounted for. During testing this summer an internal malfunction of one of the key instruments was discovered. Consequently it was returned for repair and no further tests have been completed.

Figure 1. A mobile ground-based eddy correlation test bed.

Planned Future Work:

We will continue with development of an airborne system for flux measurement. Initially we must produce both a positive instrument validation test with the repaired instrument and a positive mobile ground test. After that the plan is to proceed to rigorous airborne testing on the tethered system. Once airborne testing is complete, we will have a much better assessment of scientific data and position data integration problems and will be able to decide if more airborne tests on a tethered system are required or the system is ready to progress to a UAV based system.

Summary:

The innovative feature of our project is the 3D-measurement of H_2O and CO_2 from a small UAV. This could change the way we measure and understand H_2O and CO_2 carried in our atmosphere, and thus Goddard can take a leading role in this field. Our criterion for success is the construction of a small system that can record meaningful data from a small UAV. A technical hurdle is developing an inertial measurement system small enough to be carried on a small UAV.

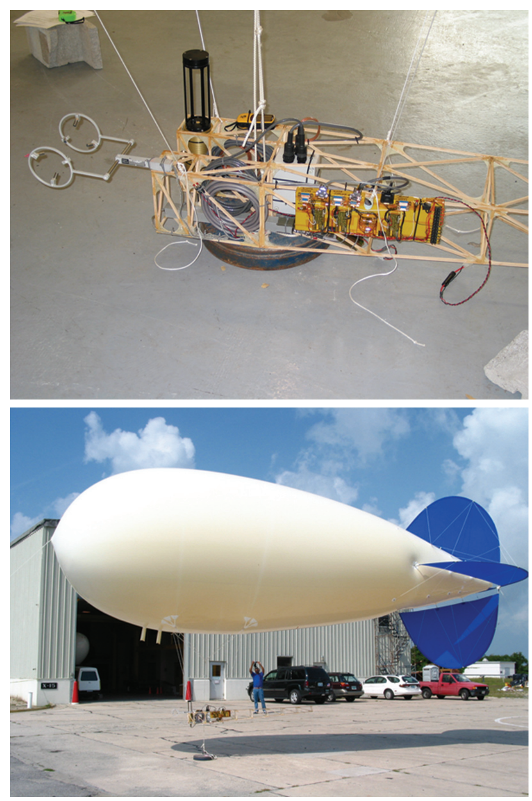


Figure 2. A blimp-based eddy covariance system deployed in August 2003.

Modeling Urban Land-Atmosphere Interactions

Principal Investigator: Christa D. Peters-Lidard (Code 974)

Co-Investigators: Menglin Jin (UMD)

Initiation Year: 2003

FY 2003 Authorized Funding: $50,000

Actual or Expected Expenditure of FY 2003 Funding: GEST $18,000; AMS publications page charge, $2,000; University of Maryland, $30,000

Status of Investigation at End of FY 2003: To be continued in FY 2004 with funds remaining from FY 2003

Expected Completion Date: March 2004

Purpose of Investigation:

The purpose of this investigation is to develop a NASA capability to model land-atmosphere interactions for urban areas, at about one kilometer in scale. Land-atmosphere interactions refer to the exchange of water, heat and momentum (such as wind) between land and atmosphere. These affect weather and related phenomena. All of the current models used by NASA and other science institutions for land-atmosphere interactions (at the time this project was initiated) do not take into consideration urban areas, which globally comprise only about 0.18% of total land area. However, emerging high-resolution modeling systems such as the Land Information System require urban modeling. Urban-scale land surface modeling is also critical for Goddard's and NASA Earth Science Enterprise's goals to understand and predict the observed effects of recent and future urban population shifts on precipitation, aerosols, and temperatures. Urban areas are clearly different from rural areas: For example, pavements alter the flow of water and black asphalt absorbs solar radiation. In essence, we aim to construct models to simulate the effect of urban areas on land-atmosphere interactions based on images from space and equations of momentum, energy and water dynamics.

Accomplishments to Date:

Our results were reported at the Fall 2003 AGU meeting and will be presented at the 2004 AMS Annual Meeting. Our FY 2003 research plan included two components: estimating urban land surface properties and modeling urban land surfaces. Towards the former, we have utilized MODIS products to estimate urban albedo, emissivity, Leaf Area Index (LAI), and surface temperature, including re-projecting and co-registering these products with a Geographic Information System for the Houston area with assistance from a NASA Academy student intern, Miguel Roman. However, we have not been able to reliably determine the critical urban parameters of impervious areas (such as pavement, which alters the way water is absorbed by the land) and building height and density from operational NASA platforms.

We have integrated a prototype urban module into the GSFC Land Information System. Initial results from this model indicate that the energy balance of an urban area is sensitive to urban parameters, as shown in figure 2, which illustrates the aggregate difference in surface temperature for Houston as predicted by our Urban Model (Case 1) compared to the Control, which uses default Community Land Model (CLM) parameters for Houston.

Planned Future Work:

Next generation land surface modeling and data assimilation systems e.g., Land Information System (LIS) will need to model and to assimilate on a one-kilometer or finer global grid that can resolve urban areas and gradients of urbanization. We will be giving talks at the AMS to report on our exciting findings. We also anticipate that the work will lead to a follow-on proposal for an Urban Data Assimilation Project, which could ultimately form the basis for an Urban Observing Mission.

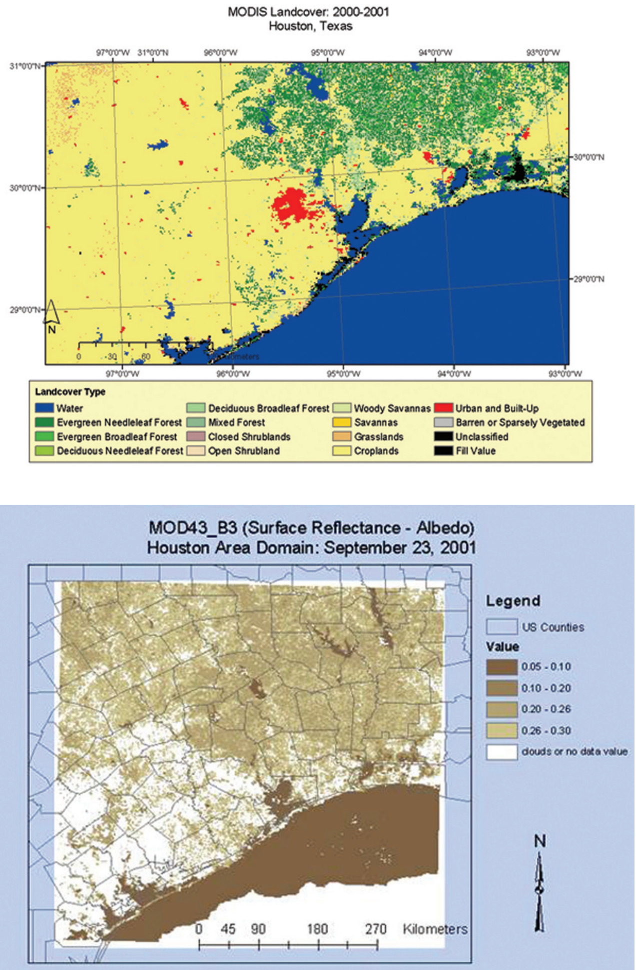
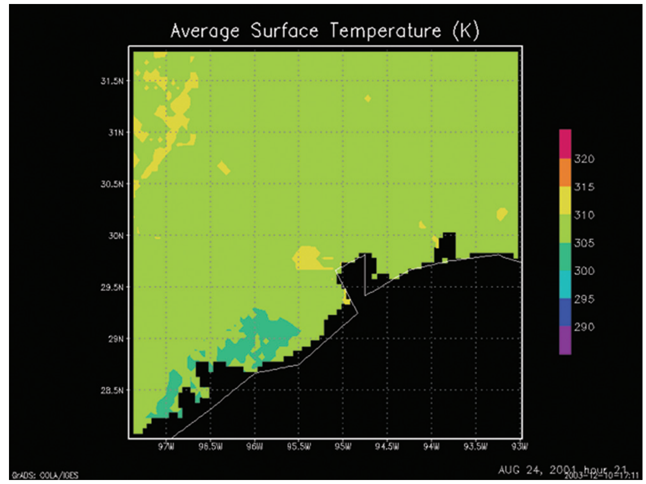
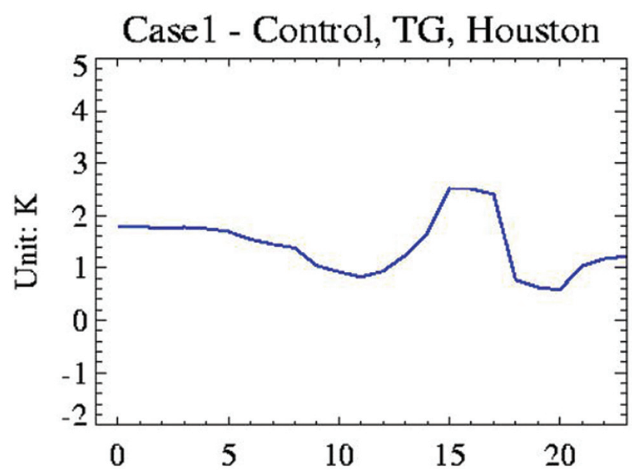


Figure 1. Houston-area landover and albedo from MODIS.



(a)



(b)

Figure 2. Houston-area surface temperature. (a) Area image at 1800 local time from Land Information System with Urban model and (b) Time series (in hours) showing the temperature difference (in Kelvin) from urban model minus control without urban model.

Summary:

This project combines NASA's strengths in MODIS-based land surface observations and global high-resolution land-atmosphere modeling with the Land Information System. MODIS (Moderate Resolution Imaging Spectroradiometer) instruments on satellites view the entire Earth surface about every two days to improve our understanding processes occurring on the land, in the oceans, and in the lower atmosphere. Similarly, the Land Information System integrates information from NASA sensors like MODIS with models that predict terrestrial water, energy and bio-geophysical processes for applications in weather and climate prediction, agricultural forecasting, water resources management, hazard mitigation and mobility assessment. Our project is unique in that it will provide an ability to observe and to model urban land-atmosphere interactions on a global basis. This has only recently been made possible with the development of the 1-km Land Information System. NASA Goddard would benefit from such modeling capability, which is absent among major U.S. land-atmosphere modeling centers, namely the National Center for Atmospheric Research, the National Oceanic and Atmospheric Administration, and the Geophysical Fluid Dynamics Laboratory. Modeling urban land-atmosphere interactions depends on modeling the surface energy, water and momentum balances. We have focused on MODIS-based estimates of parameters that impact the energy balance, such as albedo, emissivity and leaf area index. Our criterion for success is to represent effectively the observed effects of urban areas on surface temperatures, runoff and winds. However, to model runoff properly, we must effectively incorporate estimates of impervious areas (such as pavements) and building heights and density. This remains our greatest technological challenge due to the lack of globally available observations of these properties.

Frozen Hydrometeor and Snowfall Inference from Millimeter-wave Radiometry

Principal Investigator: Gail Skofronick-Jackson (Code 975)

Co-Investigators: Min-Jeong Kim and James Weinman (University of Washington)

Initiation Year: 2003

FY 2003 Authorized Funding: $36,000

Actual or Expected Expenditure of FY 2003 Funding: $36,000 grant to support Min-Jeong Kim, a graduate student

Status of Investigation at End of FY 2003: Transitioned to funding from NASA Headquarters

Expected Completion Date: FY 2006

Purpose of Investigation:

Although most global precipitation occurs as rainfall, snowfall plays a significant role in northern latitude hydrological cycles. One of the most important challenges for the future is to detect snowstorms from space. This study developed one of the first non-oceanic snowstorm estimation algorithms. Over land, the challenges are especially great: (1) satellite observations used for rainfall estimation are rather insensitive to frozen particles, (2) land surface characteristics can contaminate the observations, and (3) the relationships between the physical properties of frozen hydrometeors (for example, snow and hail) and passive brightness temperatures are not well understood. This work relies on millimeter-wave frequencies to observe the snow in the atmosphere. These frequencies are often advantageous because not only are they sensitive to frozen particles but they are also very sensitive to water vapor (almost always present in the atmosphere). Thus, they obscure the underlying surface by taking advantage of water vapor screening. This study presents a physical model of radiation from frozen particles at millimeter-wave frequencies that is used to infer snowfall rates over land. The retrieved snowfall rates are qualitatively validated against ground-based radar observations of the same March 5-6, 2001, New England blizzard.

Accomplishments to Date:

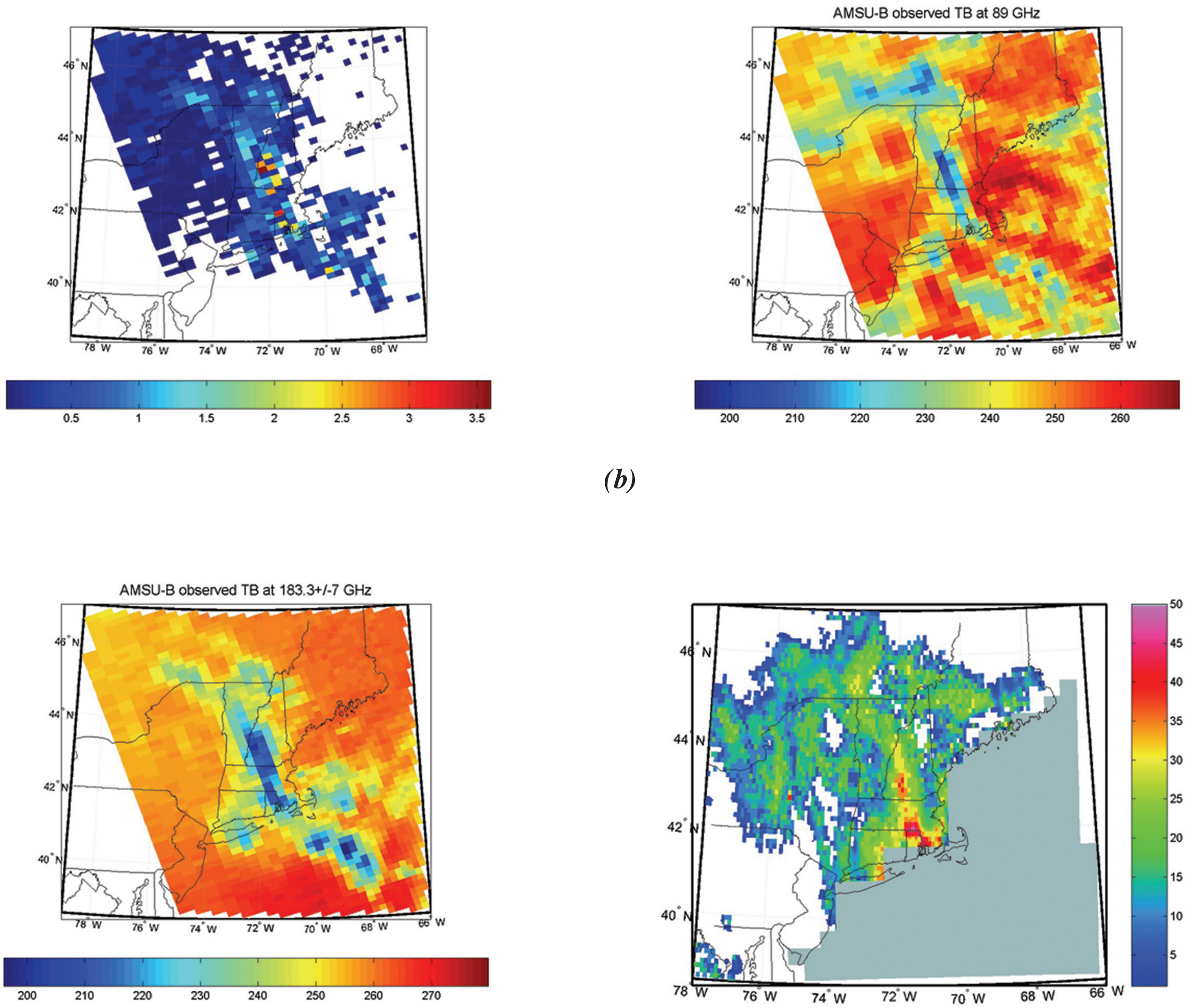
A physically-based retrieval algorithm using Advanced Microwave Sounding Unit-B (AMSU-B) observations at 89, 150, and 183.3 ±1, ±3, and ±7 GHz was developed to estimate snowfall over land. Figure 1a shows a composite of the National Weather Service (NWS) operational weather radar reflectivity, Zeff (mm^6/m^3) obtained on March 5, 2001, at 23:00 UTC. Figures 1b and 1c show the distribution of the 89 and 183.3±7 GHz brightness temperatures (TB) measured from AMSU-B at 23:02 UTC on March 5, 2001. The 89 GHz image shows surface features not evident in the radar and 183±7 GHz images.

The retrieval algorithm relied on a multi-parameter cloud model to generate the vertical structure of a snow cloud, including snow mass, snow particle effective diameter, and water vapor. Ground-based attenuation measurements were used to characterize the equivalent sphere snow particle size used herein. For each pixel in the image, the multi-parameter cloud parameterization that produced calculated brightness temperatures that best fit the AMSU-B observations was selected as the retrieved snow mass profile. It is evident that the spatial distribution of the retrieved snowfall mass in figure 1d is qualitatively similar to the radar reflectivity displayed in figure 1a. Figure 2 presents the relationship between radar reflectivity in figure 1a and retrieved snow mass in figure 1d converted to rain rate. While this is not a rigorous validation of the retrieval, it does show that this physical model enables retrievals to fall well within the bounds of existing measured and empirical relationships.

We have completed several articles and presentations of our results, including:

* G. M. Skofronick-Jackson, M.-J. Kim, J. A Weinman, and D. E. Chang, 2003: A Physical Model to Determine Snowfall over Land by Microwave Radiometry. (Accepted by IEEE Trans. Geosci. Remote Sens., Dec. 2003)

* Kim, M.-J., G. Skofronick-Jackson, and J. A. Weinman, 2003: Intercomparison of millimeter wave radiation transfer models. (Conditionally accepted to IEEE Trans. Geosci. Remote Sens., Nov. 2003)



(a) *(b)*

(c) *(d)*

Figure 1. (a) Radar reflectivity (dBZ) obtained from the NWS radar and AMSU-B brightness temperatures at (b) 89 GHz, (c) 183+7 GHz, and (d) retrieved snow mass at a 20m altitude.

* G. Skofronick-Jackson, E. Holthaus, J. Halverson, G. Heymsfield, R. Hood, B. Lambrigtsen, 2003: Microphysical characterizations of ice in Hurricane Erin for Wideband Passive Microwave Comparisons, (Submitted to J. Atmos. Sci., Dec 2003). [Eric Holthaus was a 2003 summer student resulting from this DDF.]

* Kim, M.-J., G. Skofronick-Jackson, and J. A. Weinman, 2003: Intercomparison of millimeter-wave radiative transfer models. Proceedings, IEEE International Geoscience and Remote Sensing Symposium (IGARSS), Toulouse, France, 21-25 July. (Poster Presentation)

Planned Future Work:

The retrieval algorithm developed during DDF FY 2003 provided us encouraging preliminary results showing that it is possible to estimate snowfall over land with space-borne passive millimeter-wave measurements. However, the electromagnetic characteristics of frozen hydrometeors are still poorly understood, and snow microphysics properties such as size distribution, density, and habits (characterization of crystral type) -- which are rarely measured in situ --were not employed in the current algorithm. Greater detail in the snow characteristics will be allowed through the use of more complex snow distributions, and more appropriate electromagnetic models will be employed. Furthermore, the convergence criteria for the algorithm will be improved along with additional theoretical studies. This will lead to an improved retrieval algorithm.

Summary:

Our project's innovative features are the use of millimeter-wave frequencies to estimate precipitating snow and the use of an equivalent-sphere snow model that preserves both the volume and surface area of the original particles. The potential payoff to Goddard will be the ability to measure global precipitation in northern latitudes and polar regions and to have increased effectiveness for the Global Precipitation Measurement (GPM) satellites. Our criterion for success is developing an algorithm that would enable snowfall estimate over land with space-borne passive millimeter-wave measurements. Technical risk factors are the unknowns about the snow size, shape, and density.

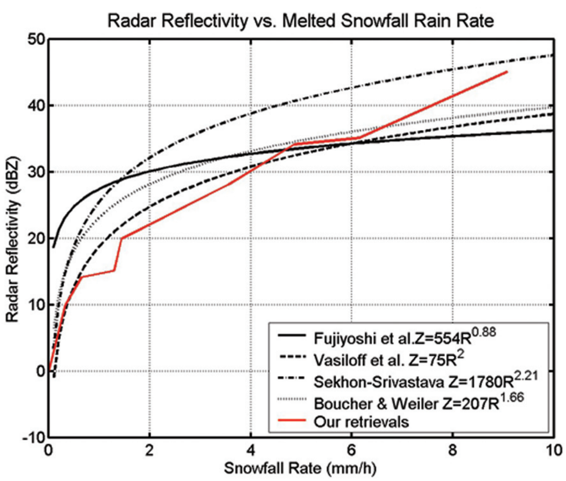


Figure 2. Measured reflectivity versus melted snowfall rate inferred from retrieved snow mass shown in Figure 1d and compared to Fujiyoshi, et al., 1990; Vasiloff et al, 2000; Sekhon and Srivastava, 1970; Boucher and Weiler, 1985.

EDUCATION

Remote Sensing Earth Science Teacher Program (RSESTeP): A Model Plan to Share UAV Technologies with Educational Communities

Principal Investigators: Patrick Coronado (Code 935), Sallie Smith (130.3)

Co-Investigators: Kelvin Brentzel (935), Geoff Bland (972), Ted Miles (972), David Herring (913) Ron Ernst (130.3), 17 JASON Project Pilot Program Teachers from 11 states

Initiation Year: 2003

FY 2003 Authorized Funding: $25,000

Actual or Expected Expenditure of FY 2003 Funding: In-house hardware and MPS, $20,000; GST contract, $5,000

Status of Investigation at End of FY 2003: To be continued in FY 2004 with funds remaining from FY 2003

Expected Completion Date: December 2004

Purpose of Investigation:

The Remote Sensing Earth Science Teacher Program (RSESTeP) has developed and is now piloting a program demonstrating how science teachers can use local NASA equipment and data to conduct real Earth Science with their students. The program employs NASA's Earth-observing satellite data, the cutting-edge technology of NASA's Uninhabited Aerial Vehicles (or UAVs, model airplanes with video and digital cameras and a thermal sensor), and ground-truthing equipment. These are used to implement teacher/student-planned Earth Science missions with help from local American Model Club Association (AMA) remote-controlled-plane pilots and scientists. Through RSESTeP, these science teachers with signed consent from their principals submit preliminary mission plans for conducting local Earth Science missions. Teachers selected to participate commit to a full week of NASA training. They receive instruction by experts in the basic principles of remote sensing, satellite data analysis and interpretation, UAV assembly, payload operations and safety protocols, and instruction in how to collect ground-truthing data. Based on preliminary mission topics, teachers are also scheduled to meet with specific NASA Earth scientists who provide mission feedback and suggestions and help locate appropriate satellite data products.

Accomplishments to Date:

We implemented all ten teacher/student missions. This began with the construction of two customized Earth Science education research UAVs by Wallops Observational Lab engineers, who designed each plane to carry multiple imaging systems on a small, hand-launched, battery-powered platform. Designed for student involvement, the planes have added safety features such as separate pilot and student payload powering switches. They also include a second radio control system so students may safely operate payload functions while the AMA pilot is flying the plane. A microchip/servo response system designed by a member of the Goddard Directional Readout Laboratory has been added to the payload digital camera and has been programmed to take pictures every five seconds during educational UAV mission flights to provide students will ample data for classroom analysis. Both planes have downlink data-monitoring equipment enabling students the ability to monitor visible and thermal UAV data as it is collected in the field.

Figure 1. NASA customized educational UAV payload, saftety switches, and pilot and student payload controls.

Figure 2. Teachers training for satellite data analysis, UAV protocols and ground-truthing.

We also trained 17 JASON Project teachers from 11 states, who submitted preliminary ideas for local student Earth-observing satellite, UAV, and ground-truthing missions. (The JASON Project is a national multidisciplinary education program.) The teachers voluntarily came to Goddard in August 2003 for a full week of remote-sensing principles, satellite mission science and product interpretation, and UAV and ground-data-collection training. The teachers were individually paired with Goddard Earth Science Enterprise scientists. The NASA/JASON RSESTeP teachers also are voluntarily helping to develop the RSESTeP Module, a step-by-step guide for future program duplication that will include sample Earth Science missions implemented by the JASON Project teacher participants this year.

In the first RSESTeP mission, Elizabeth Larwa, a fourth-grade teacher, and her science club students at Spencer Elementary School in Brighton, Michigan, teamed up with two local AMA Hamburg Flyer's pilots and a Sea Grant research scientist from Michigan State University. They used NASA satellite, plane and ground resources to monitor invasive purple loosestrife vegetation and beetle release efforts in Michigan. Involving educational communities and the general public in NASA exploration and discovery became reality with support from the township of Brighton, teachers, students, parents, pilots, and the media.

A second mission was led by 7th- and 8th-grade teachers Dee McLellan and Carla-Rae Lange and their students at Meadow Creek Christian School and Jackson Middle School in Andover, Minnesota. They used NASA Terra/Aqua satellite data products, UAV technologies and ground tools to monitor snow cover, albedo and visible reflectance. With mission planning guidance from Goddard snow expert Dorothy Hall, the students collected data related to snow cover and the Earth's radiant budget as well as expected Minnesota spring melt water supply and flooding events. Fifty students and their parents, as well as the Anoka County R/C club, participated in the field mission, which entailed basic remote sensing, satellite interpretation, and measuring Earth's radiant budget and albedo. Two Anoka R/C club pilots and the local television meteorologist conducted presentations on the principles of flight and snow-pack / water equivalency. A remote-sensing scientist from the University of Minnesota is working with the students of both schools in analyzing the data with the NASA Goddard Observatory ICE (Image Composite Editor) Tool analysis software. Again, the community, pilots, teachers, students, scientist and the media participated. Other NASA RSESTeP missions included using NASA satellite, UAV and ground truthing instruments to monitor changing Wetlands in North Carolina, weather patterns in Michigan compared to Mars, monitoring Karst Geologic features in Minnesota, and mapping vegetation and tributaries along the South Carolina Congaree River.

Planned Future Work:

Future plans include developing the RSESTeP Module, which will provide detailed information about all aspects of the RSESTeP for possible duplication beyond the original DDF. Elementary, middle and high school RSESTeP Earth Science missions implemented during the pilot will be included in the module outlining what activities and resources were used for the various Earth Science missions.

Figure 3. A primary goal of the RSESTeP is to put cutting edge NASA technologies into the hands of teachers like 4th grade teacher Elizabeth Larwa, first to use NASA's customized ED UAV to implement the first RSESTeP mission with students in Brighton, Michigan.

Figure 4. Ground instrument and UAV thermal and visible data collected by students during local missions are correlated with satellite data of the same area in post mission classroom analysis.

Figure 5. Entire communities enthusiastically come out to participate in local NASA RSESTeP Earth Science Missions.

Summary:

The innovative features of the RSESTeP include (1) customized UAV Education Earth Science Research Planes built by Wallops Observational lab engineers and (2) required pairing of teachers with not only NASA but AMA pilots and scientists. This allows teachers the opportunity to transform curriculum paper studies to real field research while establishing a major career pipeline by exposing students and the community to the opportunities that exist in the fields of science, engineering and technology.

The success criteria for the RSESTeP includes: (1) the successful design of UAV technologies for educational purposes; (2) the successful implementation of the remote-sensing Earth Science missions planned by the JASON teachers using NASA science and technologies; and (3) the development of the RSESTeP Module. The RSESTeP has already proven to be a valuable asset to NASA in its demonstrated ability to achieve educational goals 6 and 7 of NASA's strategic plan. In this program, teachers, students, parents, pilots, scientists and members of the community engage in the experience of exploration and discovery, participating in a local mission that is based on NASA EOS science and implemented using NASA resources that aid in the proficiency of science and increase awareness of NASA career pipeline opportunities. The RSESTeP, if supported beyond initial funding, could be used in the Agency's identified top-priority educational programs, such as the Explorer Schools and JASON Project.

Exploratory Collaborative Study: Innovative Approach to Mathematics Education

Principal Investigator: Garcia Blount (Code 547)

Co-Investigators: Janie Nall (120, EduTech), Irina Nelson (IPA, Salt Lake Community College)

Initiation Year: 2003

FY 2003 Authorized Funding: $10,000

Actual or Expected Expenditure of FY 2003 Funding: not yet spent

Status of Investigation at End of FY 2003: To be continued in FY 2004 with funds remaining from FY 2003

Expected Completion Date: December 2004

Purpose of Investigation:

This project explores a unique approach to mathematics instruction. It seeks to merge the use of Montessori materials with relevant NASA and aerospace-related activities into teaching modules for use in the non-Montessori environment of the Baltimore inner-city Rosemont Elementary public school. The Montessori mathematics teaching methodology is highly recognized for enabling the child to learn and to understand abstract mathematical concepts by working with concrete materials, an approach that builds a solid foundation for abstract thinking and mastery of mathematical principles. The mathematics activities recently sponsored by NASA for the K-4, 5-8, and 9-12 levels incorporate the excitement of space as a stimulus for both teacher and student. The project addresses an important educational issue and involves an at-risk, minority population.

The project seeks to achieve its goal by initiating a collaboration among NASA Goddard, the Maryland Space Grant Consortium, Coppin State College (CSC), Rosemont Elementary School, and Washington Montessori Institute (WMI) at Loyola College of Maryland. Assessment of whether to move into the design and implementation phase is based on the institutions determination of feasibility. If the assessment is positive, then we plan to design and implement a model for integration of NASA-related mathematics activities with Montessori methodology, incorporating metrics and evaluation criteria.

Accomplishments to Date:

Explorations into the feasibility of the partnership and of the approach to teaching mathematics have been ongoing, although slowly. To date, the principal of Rosemont Elementary School, Mrs. Sandra Ashe, has tentatively agreed to a schedule that includes teacher training through the Washington Montessori Institute (WMI) over a one-year period (September 2003 to August 2004), and the implementation of a Montessori mathematics approach and materials in a test classroom in September of 2004. The Dean of Arts and Sciences at Coppin State is now more fully on-board with this project, due to a greater understanding of the goals and the methodology to achieve progress. Effort has been spent on relationship building with and among the partners, which has proven critical to forward movement. A visit was made to the Washington Montessori Institute that gave the partners from Coppin and Rosemont an opportunity to see the proposed Montessori materials and to gain a greater understanding of the mechanics of instruction. The level of acceptance and receptivity to both concept and mechanics was greatly enhanced during that visit. A follow-up visit to a Montessori classroom (Patuxent Montessori School in Bowie, Md.) was requested and will be scheduled in the near future. All are in agreement that we need to abide by the Maryland State Standards and limit the pieces of equipment we use to specific skill sets.

Planned Future Work:

A calendar for teacher training will be finalized for the Rosemont teachers. This involves scheduling among the WMI, Coppin and Rosemont staff members. The training will take place at both the WMI facility and at Rosemont. An implementation date of September 2004 has been agreed, provided the training is completed and the teachers are ready. The Coppin partners will identify appropriate graduate students for interview by both Coppin and Rosmont since they will be involved with both sides in an integral way. The graduate student will be doing research, and documenting progress as well as the methodology of the Montessori approach to mathematics instruction within a non-Montessori environment. The WMI has indicated a Baltimore native in their program who is very supportive of the project and who all parties felt would be ideal to interface with the teachers, both in the classroom and during their training at the WMI. The Goddard staff working with this project will commit to facilitating the progress of the project by serving as a liaison among all partners, and structuring a set meeting date every other week. It is felt that effort at this level is required in order to continue forward progress.

Summary:

Our project's innovative feature is a unique approach to mathematics instruction in a setting outside of its standard environment (a Montessori elementary school). Increasing the fundamental understanding of mathematics in elementary age children fits with the overall educational goals of both Goddard and NASA in that we are exploring preparation of a more mathematically adept future workforce and public at large. Evaluation metrics are to include pre- and post- assessment of appropriate mathematical understanding, our criterion of success. As for technical risk factors, there was the need for cooperation among disparate institutions, as well as many details to be worked, including possibilities for sustaining support after the exploratory phase if deemed worthwhile. The greatest hold-up has been the lack of a prior relationship. The effort toward a cohesive group should allow the original project to move forward at an agreed pace during the next year. A training calendar for the Rosemont teachers has been discussed, but remains to be finalized. While unfortunate, the delay has proven the tentative nature of the original proposal. The background work has set the stage for the training for the next year.

Student Experimenters Virtually Experiencing NASA (SEVEN)

Principal Investigator: Chuck Brodell (Code 870), Berit Bland (CSC/BBCO)

Co-Investigators: Dave Wilcox (549), Tom Taylor (589), Greg Waters (569), Don Bosman (ODIN)

Initiation Year: 2003

FY 2003 Authorized Funding: $20,000

Actual or Expected Expenditure of FY 2003 Funding: $17,000 for hardware purchases; $3,000 for CSC

Status of Investigation at End of FY 2003: To be continued in FY 2004 with funds remaining from FY 2003

Expected Completion Date: March 2004

Purpose of Investigation:

The purpose of this project is to improve the effectiveness of "virtual" interaction between NASA and students in support of hands-on educational projects. The virtual interaction allows students to work directly with the NASA team without leaving the classroom. The primary goal is to provide support to student flight project activities. This project expands upon the concept of "virtual integration" developed through student participation in the Space Experiment Module (SEM) program at the Wallops Flight Facility (WFF). Through technology improvements in hardware and software, we will witness an increase in the level of student excitement, the number of students involved, and an overall positive impact. Student engagement will be increased through improvements in two-way communications, remote video control, and improved video/audio quality. The new system will be portable, allowing student access to many more facets of NASA operations. The system will be available to all WFF student projects. This approach to student involvement maximizes participation throughout the country and allows access to all geographical locations.

Accomplishments to Date:

Soon after the selection notification of the SEVEN proposal, a technical team was established including software people, network experts, electrical support, and the educational projects support team. The team investigated different routing options including those available through Greenbelt. Several brainstorming sessions were conducted to determine the most effective and efficient technical approach. Preliminary testing of Firewire video input was conducted with positive results in speed and clarity. Once the technical approach was developed, system requirements were researched and defined. Hardware/software combinations were established and all purchase orders were submitted to procurement. Procurements include: web cast server, laptop with Firewire video input, improved video camera, web cameras, Realnetworks helix software, and Polycom speaker phones.

All procurements were submitted at the earliest date in July 2003, immediately following the shutdown during the transition to the new financial system. Due to procurement delays, only the video laptop, speakerphones, and a couple web cameras have arrived as of end of November 2003. Delayed arrival of the software and sever have precluded any system setup and testing. The laptop for video capture has been accepted, checked out, prepared for network connection, and is awaiting systems testing.The new Helix server will allow transmission of any of the three main streaming video formats (Real, Quicktime, Windows Media) using only one server. This reduces software costs and complexity, making web casts more flexible and accessible to customers. Helix has a new applications program interface (API) that allows development of custom data streaming applications. The Helix server provides the capability of splitting web casts by sending a stream to a remote server that rebroadcasts the stream. This rebroadcast reduces bandwidth requirements on the originating server and allows higher-speed connections to the ultimate customers. The WFF educational projects lab has been relocated into a refurbished building with a dedicated work area. The lab has been set up for web casting capability. A centrally located work area with a dark blue solid colored back drop has been set up for optimal web casting. The solid backdrop minimizes background motion and allows for a smoother more efficient video transmission.

Planned Future Work:

Current plans are to setup, configure, and connect system components as the hardware and software arrives. The first set of system testing will be conducted internal at WFF. Testing will expand to Greenbelt and other external sites. Testing with external customers will gradually increase in the level of complexity. Web casting of several upcoming events and activities are on schedule and will be conducted with the new equipment. The remote internet cameras will go online soon after web casting systems are tested allowing student control of video during lab activities. Portability will be tested during upcoming activities including the NASA Student Involvement Program (NSIP) flight week events in June 2004. It is anticipated all systems should be operational in the March time frame. These capabilities are planned to be integrated with a Student Ground Network that is currently under proposal review.

Summary:

This project is innovative because it allows direct two-way interaction between students in the classroom and NASA, independent of geographical location. It allows maximal student involvement at minimal cost. It lets student groups partner and share their projects with those back at their school as well as students at other schools. The payoff to Goddard is extensive involvement with student groups. This involvement benefits the students, helps inspire them to technical career paths, and provides positive exposure for NASA. This project is in alignment with the goals of the new NASA Education Office and will help establish a working relationship with this young organization. The primary criterion for success is to get a functioning, portable, web-casting system used in support of student projects. The system needs to be an improvement to current capabilities. A secondary criterion is improving two-way communication and remote controlled video. Technical risks include system compatibility problems and possible firewall/security complications. We also need to ensure end-user applications are versatile and accessible to all users independent of their connection and/or hardware configuration.

Goddard Space Flight Center / University of Maryland Eastern Shore Education Outreach for Remote Sensing Operations at Wallops Flight Facility

Principal Investigator: Russell Dufrene (Code 598)

Co-Investigators: Douglas R. Levin (UMES), Jessica Thompson (598), Carl Snow (598)

Initiation Year: 2003

FY 2003 Authorized Funding: $25,000

Actual or Expected Expenditure of FY 2003 Funding: Marine Student Association, Pocomoke High School, $2,000; Marine Technology Club, Robinson High School, $2,000; VideoRay, $16,000; robotics and misc., $5,000

Status of Investigation at End of FY 2003: To be continued in FY 2004 with funds remaining from FY 2003 and possible DDF FY 2004 funding

Expected Completion Date: October 2004

Purpose of Investigation:

The goal of our project is to give students the opportunity to experience discovery. We believe that the spark that we experience as part of the NASA family and as scientists can be addictive. The students are learning that discovery is exciting in many areas, including robotics, science, and even the learning process itself. Another goal is to establish an ongoing partnership with high school teachers to enrich the school science and technology curriculum through the implementation of modern hands-on projects. These projects include building land-and water-borne robotic kits and utilizing remotely operated vehicles to collect and analyze geographically referenced data of all kinds. The program teaches high school students the process and experience of science by placing them in the roles of scientists, explorers and discoverers as they prepare for technology competitions.

Accomplishments to Date:

We accomplished several of our goals. We are initiating relationships between high schools, WFF and the University of Maryland Eastern Shore (UMES). Relationships were established with two high schools, Pocomoke Senior High, a local school in Maryland, and the Robinson High School, in Tampa, Florida. Kristy Loman Chiodo at the Robinson High School in Florida is developing the curriculum for the Remotely Operated Vehicle (ROV) that will be consistent with National Standards. Chris Miles will participate locally from Pocomoke High School to help integrate the Stiquito Robotics and remote vehicles.

This year, the goal to incorporate student involvement in current WFF/UMES research projects was achieved in part through two UMES undergraduate students, Tina Drew and John Wood. These UMES students were recruited through

Figure 1. Development of terrestrial and aquatic robotics for shoreline data collection.

Figure 2. Surface Operated Vehicle Development and Test.

our relationship with Dr. Dabipi, the chair of Engineering and Aviation Sciences at UMES, and Lisa Johnson in Code 120 at WFF. Tina Drew obtained ownership of the research and development of the Flexinol/Nitinol Stiquito Robot from Institute of Electrical and Electronics Engineers (IEEE) Computer Society. She built a working, crawling robot and identified problem areas for younger students. She found the robot was too fragile for K-12 students, making it difficult to complete without compromising various parts. The decision was made to modify the kits so that the technical skills required are appropriate for a spectrum of student levels from K-12, higher education, and other informal educational forums. John Wood was responsible for the refurbishment and electrical design of the Surface Operated Vehicle (SOV). It will be able to map water depths and collect and analyze water samples remotely.

The work proposed for FY 2003 started late. The 2002-2003 school year finished before materials and supplies were ordered and volunteers were not selected until the summer of FY 2003. These delays have evolved as real-life experience for everyone involved, and the quest and discovery remain exciting as well as the technology.

Planned Future Work:

We want to continue the research plan presented last year with the ROV, SOV, and Stiquito Robot concepts. We believe that the students are sparked with interest in discovery and so far this spark in growing into the basis for all of science, which is the capability to ask and pursue questions. We have requested some additional funding to provide advancements for autonomous operation in the ROV, a robotic arm for the ROV, additional capabilities for the SOV (Telemetry, Satellite communication), and YMCA pool rental for training and competition events. We are also looking to add DVD recording for the real-time video, which could lead to web-based program enhancements. It is important that we purchase materials for constructing a larger Stiquito Robot so that younger students can use the kits.

School systems will be invited to appoint teacher advised student teams to learn about these systems. Under supervision, they will learn to assemble/disassemble robots and also learn how to pilot the SOV/ROV in a controlled environment, such as the YMCA pool. The Pocomoke River Exploratory will be the local on-site laboratory for teaching, robot assembly, and field application. Upon "graduation" from

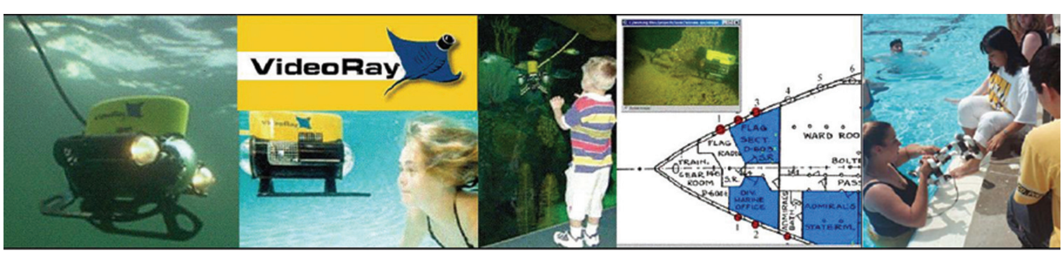


Figure 3. Learning how to use the Remotely Operated Vehicle for exploration.

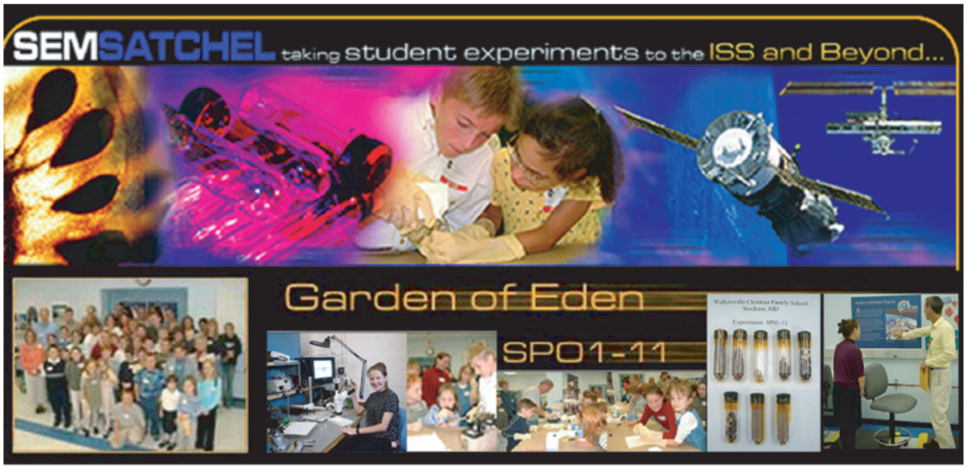


Figure 4. "Garden of Eden" Space Station Experiment with Code 546.

the pool, students will be invited to apply the technology to the Stevenson Pond site near Winter Quarters in Pocomoke City.

The participating school systems will be invited to join a technology competition with awards incentives. Each team will be asked to create an expedition/mission that would involve the SOV and ROV in a scientific venture within Stevenson Pond. The designs will be judged for merit/application by an appointed panel. The selected designs will be invited to implement their missions on site. Several types of competitions are envisioned; all involving design, development, and operation stages. We feel that the competition is important because it encourages team involvement between students and reinforces robotic and system concepts learned in the curriculum. The students will also participate with the Walkersville Christian Family Homeschool students Space Station project "Garden of Eden" in FY 2004. This experiment involves brine shrimp cysts, Triop cysts, and a variety of garden vegetables that will have remained aboard the Space Station for many months. Questions like, "Does Mars or the Moon have cysts that will grow in water?" were asked by the homeschoolers. The process of growing the Space Station cysts and seeds, and comparing the results against the samples kept on Earth will give all the students further experience and excitement in scientific processes and discovery.

This NASA initiative dovetails smartly with a three-year NOAA funded program that is integrating data collection and analysis programs within six Delmarva High Schools. As Co-Principal Investigator, Dr. Levin is responsible for showing secondary school educators and their students how to use various technologies in field and laboratory settings to collect, share, and analyze environmental data sets. The schools that are already onboard through this program will be used for this outreach program.

Summary:

This project promotes interest in science ventures and discovery among students and educators and also provides them with a unique, real-life experience with the feeling of responsibility and "ownership" in NASA's research efforts. We feel this research is beneficial to NASA and Goddard because it serves to inspire the next generation of explorers (NASA Mission III), and it furthers the mission and vision of Code N by aligning science and education outreach in both the NASA Earth Science and Education Enterprises. Both Goddard and UMES are collaborating to provide hands-on science and exploration to align with the "As Only NASA Can" theme. The innovative elements of our project are the robotic exploration vehicles (SOV, ROV, and Stiquito Robot). These systems help initiate thoughts, questions, and discovery. The payoff will be the collection of data sets for Dr. Levin's NOAA work, the real-world experience and education for the students and teachers, and most important the possible recruitment of new scientists and engineers as the students become excited and exposed to our world through this program. Our criterion for success is to garner a high participation level of students and teachers and ultimately find these students at NASA or space-related industries or in technical occupations. Some risk factors are technology, funding issues, school participation and student involvement.

The Baltimore Student Sun Photometer Network

Principal Investigator: Brent Holben (Code 923), and Elissa Levine (923)

Co-Investigators: David Giles (SSAI), Terry Aquino (923), Izolda Trakhtenberg (SSAI), Asad Ullah (SSAI), Doug Fireside (Baltimore City), and UMMS Breathmobile program

Initiation Year: 2002

Aggregate Amount of Funding Authorized in Earlier Years: $25,000

FY 2003 Authorized Funding: $35,000

Actual or Expected Expenditure of FY 2003 Funding: In-house equipment and supplies, $5,000; SSAI contract, $27,500; Westover contract, $2,500

Status of Investigation at End of FY 2003: completed

Expected Completion Date: completed

Purpose of Investigation:

As an education and outreach project, the purpose of the Baltimore Student Sun Photometer Network (BSSN) was to enhance the science, math and technology skills of children in elementary, middle and high schools in Baltimore and vicinity, to improve their understanding of their local environment, and to involve them as partners in this scientific investigation. The BSSN project provided students in 20 schools throughout the Baltimore area with hand-held sun photometers and breath peak-flow meters. Students made daily measurements of atmospheric aerosols and cloud cover in order to relate the presence of particulates (which have been strongly correlated with asthma) to lung function on a real-time basis. Data were then uploaded to the project web site (http://bssn.gsfc.nasa.gov) by students, where they are currently stored and can be viewed and retrieved. Learning materials and other information were also developed for students and teachers to access from the project website.

From the science and technology perspective, our plan was to provide the first comprehensive urban aerosol retrieval using remotely sensed data and spatially distributed ground validation, and to improve the Baltimore Children's Asthma Study data set by providing daily, local information across the region for comparison with clinical and other environmental data. In addition, we wanted to identify spatial and temporal trends in aerosol loading regionally through comparison of school retrievals, allow NASA scientists to make atmospheric corrections on a pixel level, and provide Earth Observing System / Moderate Resolution Imaging Spectroradiometer (EOS/MODIS) and Multiangle Imaging SpectroRadiometer (MISR) science teams a unique data set for validation of their aerosol products.

Accomplishments to Date:

Education and outreach: Through contacts with the Supervisor of the Office of Science and Health in the Baltimore City Public Schools and schools involved in the GLOBE and University of Maryland Medical System (UMMS) "Breathmobile" programs, we identified 20 schools (figure 1) that were interested in participating in our project. Schools from the Baltimore City metropolitan area were solicited by letter invitation and direct contact to participate in this project. Training was held for teachers and students to learn measurement protocols at the Maryland Science Center and at school sites (figure 2). Both hardcopy handouts and web-based training materials were developed to teach protocols and science concepts of the BSSN. The BSSN web site (http://bssn.gsfc.nasa.gov) contains background information on the project, a technical description of the sun photometer and data processing, electronic versions of the protocols, data submission pages, links to school data, and links to other related information. Throughout the project schools were supported by phone, e-mail, e-newsletters and school visits. Teachers were also given additional Earth science education and outreach materials to encourage students to explore science, math and technology careers. A critical mass of reliable science teachers and students are now available in the Baltimore metro area to work with NASA on this and other projects. A system for communication between schools and

NASA is also in place, including the BSSN web site, which provides a central location for disseminating information and uploading sun photometer and atmospheric data.

Science and technology: Handheld LED sun photometers were successfully upgraded to photo diodes, which increased their sensitivity by a factor of 100. This new instrument was tested in summer of 2002 by eleven high school and college students who were recruited to make measurements at various sites within the city of Baltimore. Through collaboration with the UMMC "Breathmobile" program, the students also measured lung function of volunteers within the city, in addition to aerosol optical thickness. Data results from this exercise have been processed and shown in figure 3.

Data collection from Baltimore schools began in fall of 2002. Over 600 individual pieces of data have been collected from schools in the metro area over the duration of the project. Processed data is available on the BSSN websiteResults showed that there is wide variability in atmospheric haze measurements by location around Baltimore City and between the hand-held sun photometer data and data from NASA's ground-based AErosol RObotic NEtwork (AERONET) instrument at the Maryland Science Center, indicating possible local variation across the city. In addition, there is wide variability in lung function between students across the city and within specific groups of children in a classroom. Based on the data collected to date, no clear relationship was found between lung function and atmospheric haze. However, the small sample size and inconsistency of data reporting should be considered.

An additional effort was made to coordinate student measurements with over flights of the Landsat, Terra (MODIS, MISR, MODLAND, ASTER) and EO-1 instruments. Due to inclement weather, only a small number of coordinated measurements were made. Images for the over flight dates for each of these instruments have been processed (figure 4). This work was featured on NASA's "Top Story" web site in June 2002 and on WJZ (Baltimore) TV News.

Planned Future Work:

Collaboration will be continued with committed teachers at a number of schools to continue to make simultaneous measurements of lung function and aerosol optical depth for research purposes. Follow-up and support will be minimized, however, unless additional funding is provided through other funding sources. The BSSN web site will continue to be maintained for data archive and analysis. The project leaves in place a web-based infrastructure that allows students, teachers and scientists to actively submit hand held sun photometer data through the Internet which is automatically processed and displayed through an interactive interface maintained by the AERONET program. All data past present and future and training materials are available through the website for data analysis and teaching. The website has been used by aschool system in Bangkok, Thailand, for student scientists to operate a network of handheld sun photometers during the burning season of 2003. The results are online.

Summary:

This project was innovative in that it made use of students as collaborators for research and provided a hands-on science experience for students to learn basic science concepts and research methods. Our work closely adhered to Goddard's mission in that it expands knowledge of the Earth and its environment to students and teachers by including them in an Earth Science research program using space- and ground-based technology. NASA scientists can benefit from a data set of daily, local-level aerosol loading, and this and the lung function data can be used to supplement NASA's Baltimore Asthma Project Data base. These data also provide a comparison of retrievals between schools across the region for AERONET scientists, allow NASA unique opportunity to make an atmospheric correction on a pixel level, and Earth Observing System / Moderate Resolution Imaging Spectroradiometer (EOS/MODIS) and Multiangle Imaging SpectroRadiometer (MISR) science teams a unique data set for validation of their aerosol products. This project would have been more successful if we were able to obtain regular daily measurements of aerosol optical depth and lung function. In addition, implementation of the data protocols and learning activities in the classroom that engaged students and teachers would have achieved another criterion for success. This project required consistent and committed efforts for data collection that were not always possible. In general, we found teachers to be overloaded, overworked and underpaid. Of the total number of schools interested at the start of the project, only a small number of teachers were motivated, organized, and committed to participate in the BSSN project for an entire school year. Even with the most committed teachers, it became obvious that the only effective way to engage regular data collection was to offer financial compensation for each measurement made. Students could not always collect data reliably because of school closings, classroom restraints, and inclement weather. In addition, data was only collected five days a week and not on weekends, holidays, or during the summer, as would have been preferred for more meaningful analysis of results.

The Pavilion: A Collaboration Between Art and Technology

Principal Investigator: Joseph M. Howard (Code 551)

Co-Investigators: Randall Packer (Maryland Institute College of Art)

Initiation Year: 2003

FY 2003 Authorized Funding: $4,500

Actual or Expected Expenditure of FY 2003 Funding: Projection and camera electronics, $2,000; Pavilion structure, $500; image processing computer, $2,000

Status of Investigation at End of FY 2003: To be continued in FY 2004 with additional DDF funding

Expected Completion Date: May 2004

Purpose of Investigation:

The goal of the Pavilion project is to build a scale model of the original Pepsi Pavilion presented at the 1970 Expo in Osaka, Japan. The Pepsi Pavilion was one of the first artworks and performance spaces to completely immerse a large number of viewers in an interactive environment. At its heart was a 30-meter-diameter dome mirror, subtending a full 210° solid angle, greater than a hemisphere. The visitors experienced a real image of themselves floating in the space above and around them. A real image results from the curvature of the mirror and is located in an accessible location: in this case, it is between the dome mirror and the viewer, allowing one to visually shake hands with oneself, or even pass through one's own image. (A virtual image, on the other hand, is when the image lies behind a mirror, in space where the light from the object does not travel. A common example of this is seeing oneself behind a flat bathroom mirror.) The model will recreate this Pavilion experience in a networked environment, where images are uploaded from the viewer to the Internet and projected into the 48-inch mirror dome. A camera retrieves the reflected real images, and these are processed and piped back to the viewer.

Accomplishments to Date:

Our first significant achievement for the Pavilion project was to recruit two corporate sponsors to donate our 48-inch dome mirror. Fred Silver & Co., Inc., in partnership with Replex Plastics, answered the call and contributed both time and material to deliver a modified dome mirror from their product line. This modification included new fixtures to coat the internal surface of the mirror dome (as opposed to coating the external surface for standard applications). The dome was delivered in August 2003, and an inside view is illustrated in figure 1, along with some supporting electronics for image. Following delivery we have added display and camera electronics and have demonstrated the "blooming" effect from imaging a ball at the focal point of the mirror. On the left of figure 2 is a photograph from the original Pavilion, and on the right is the model.

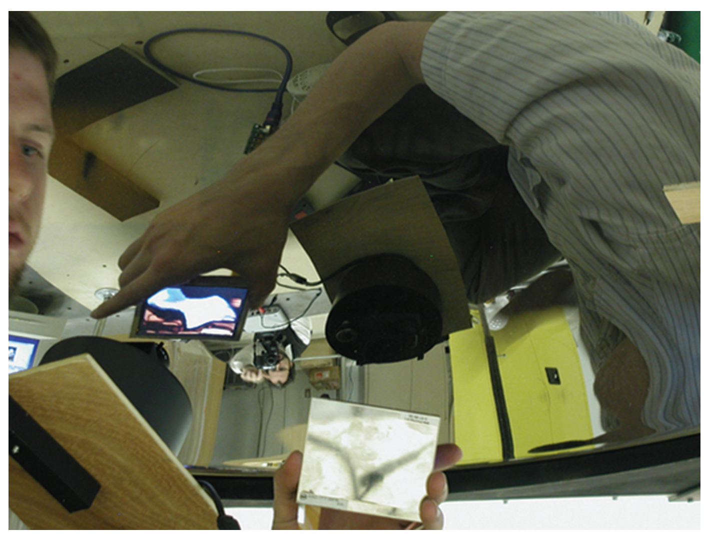


Figure 1. A view inside the 48-inch Pavilion dome mirror. Student Wes Smith (left) is holding the LCD display used for image generation, and camera for image capture can be seen on wooden platform. Co-investigator Randall Packer can be seen in the background taking external photos.

Figure 2. Comparison of images from original dome (left) and model dome (right). Both show "blooming" effect resulting from a ball placed at the focal point of the mirror.

Planned Future Work:

The next phase of the Pavilion project is to demonstrate continuous imaging within the dome as seen from a user on the internet. This process is summarized as follows: upload the image to the pavilion, project it into the dome, reflect off the mirror, capture with the dome camera, process (if desired), and download to the viewer in a continuously streaming mode. We have recruited an installation designer (Greg Kuhn) who will begin work on the external structure of the model early in 2004 for gallery viewing, which includes additional mirrors for audience to experience seeing real images as they would have within the original Pavilion.

The final phase of the Pavilion project will begin in the spring of 2004 as we preview the work here at Goddard, followed shortly after by the premier of the work at the Maryland Institute College of Art on April 8, 2004. We plan to present the work at other area colleges including George Mason and Johns Hopkins, and other museum and gallery presentations are being pursued. The initial audience of the Pavilion project will mostly consist of media and arts students, but we intend to present to the general public over the internet and through public museums and galleries.

Summary:

Our project's technical innovative feature is the real-time viewing over the Internet of images created by spherical dome mirrors. This is a novel combination of art and technology. Goddard will gain visibility through outreach to the arts community and general public in museums and art galleries, as well as over the Internet. We have two criteria for success, one technical and the other programmatic. We are aiming for closed-loop streaming images demonstrated prior to premier on May 12, 2004. And we seek follow-on funding from corporate and foundation sponsors (non-NASA Goddard). One technical risk factor is poor image quality resulting from non-spherical surface of dome, which has yet to be determined.

The Mathematics, Engineering and Science Enrichment Pre-College Program

Principal Investigator: Lisa Johnson (Code 120)

Co-Investigators: Janie Nall (EduTech Ltd), Brenda Holden (Virginia Cooperative Extension Office), University of Maryland, College Park and Eastern Shore

Initiation Year: 2002

Aggregate Amount of Funding Authorized in Earlier Years: $20,000 DDF

FY 2003 Authorized Funding: $16,500

Actual or Expected Expenditure of FY 2003 Funding: In-house, $16,000

Status of Investigation at End of FY 2003: To be continued in FY 2004 with funds remaining from FY 2003 and earlier years

Expected Completion Date: December 2004

Purpose of Investigation:

The Mathematics, Engineering and Science Enrichment Pre-College Program (MESEP) is designed to ignite high school students' interest in science, technology, engineering and mathematics (STEM) and to stimulate the students' STEM skills and their application. The underlying goal of the project is to increase the number of minorities and female students who are prepared for the rigor of university study in STEM. The program consists of hands-on learning activities, guest lecturers, and field trips at both the University of Maryland College Park (UMCP) and the University of Maryland Eastern Shore (UMES). The UMCP program focuses on exploring the math, physics, engineering and design behind roller coasters. Saturday Academies convene during the school year. The UMES program includes an eighteen-day Summer Academy and Saturday Academies. In both instances, the students receive instruction in physics, engineering, mathematics, English and analytical skills along with parallel activities.

Accomplishments to Date:

With the advent of IFM, purchase request completion has been an arduous task to say the least. To date, some PRs remain outstanding to close out the FY2002 expenditures. Due to these unresolved funding difficulties, no programs were held during 2003. With regard to both Universities, the intent is to close out any remaining purchases and to proceed with new programs during FY2004.

Planned Future Work:

As noted above, the intent is to replicate both the UMCP and the UMES programs for new student groups. Program refinements will be implemented to increase success. Plans are already underway with UMES. It is expected that UMCP will be ready to begin the new dialog in short order.

Summary:

MESEP features experiential learning. The students learn through hands-on experience rather than lecture. The projects are carefully selected based on the combined potential impact from a technical and student interest standpoint. Students are brought to college campuses in order to be exposed to that environment. Clearly, through these programs, we are inciting students interest in science, technology, engineering and math. These students will go on to apply for SHARP, Space Club Scholar, SEMAA and other NASA-sponsored programs. Through MESEP, we are inspiring the next generation of explorers. We have several criteria of success. Regular attendance is one initial indicator that the students' interest in STEM is being ignited. Improved classroom performance is another key indictor of program success. Student application for other NASA-sponsored programs would be a key success indicator.

Exploring Planetary Topography in the Classroom Using 3-Dimensional Models

Principal Investigator: John Keller (Code 691)

Co-Investigators: Herb Frey (921), James Roark (SSAI, 921), Susan Sakimoto (UMBC, 921), Stephanie Stockman (SSAI, 921)

Initiation Year: 2003

FY 2003 Authorized Funding: $19,000

Actual or Expected Expenditure of FY 2003 Funding: In-house, $13,000

Status of Investigation at End of FY 2003: To be continued in FY 2004 with funds remaining from FY 2003

Expected Completion Date: December 30, 2004

Purpose of Investigation:

We recently acquired a rapid prototyping machine that builds 3-dimensional models in extruded plastic. This is analogous to “printing” in 3-D, layer by layer. While the machine was acquired to assist in the design and development of scientific instruments and hardware, it is also fully capable of producing models of spacecraft remote-sensing data. We have demonstrated this by constructing models of the Martian topography using Mars Orbiter Laser Altimeter (MOLA) data (figure 1). The resulting topographic plastic models are visually appealing and instantly engage those who handle them. They provide significantly improved representation of the three-dimensional character of a planetary surface, which is often difficult to visualize from 2-dimensional maps. This project’s goal is to develop educational tools for teaching earth and planetary science using topographic data that has been collected by recent spacecraft missions. The tools, in the form of kits and associated lesson plans, provide aids in middle school education (5-8) where topics on landforms, solar system objects, and visualizing data are identified as core educational concepts by both the National Research Council’s National Science Education Standards and Project 2061’s Benchmarks for Science Literacy.

Accomplishments to Date:

We have developed models for a number of topographical features in analogous Mars/Earth pairs. These include: Olympus Mons / Hawaiian Volcanic Chain; Mars Polar Cap / Antarctica; Maja Valley / Grand Canyon; and Valles Marineras / East African Rift. A complete kit based on the Olympus Mons / Hawaiian Volcanic Chain pair has been developed with supporting material that covers topics in volcanism and cartography. Supporting material includes demonstration projects, question and answer exercises for the students, and teacher introduction and support. The kits have been distributed to over 50 teachers across the country who are using them during the upcoming year. We have located a manufacturer of solid models who can build the models less expensively and more quickly than we can produce them in our rapid prototyper. We completed the educational kits over the summer of 2003. This effort was led by Frank Niepold, a professional teacher intern, whose sensitivity toward real classroom dynamics and logistics has helped us to develop a usable kit. We also presented data at the Lunar and Planetary Sciences Conference (2003) and Fall 2003 AGU.

Use of the models has become a significant component of Goddard’s recent initiative to develop a relationship with the National Federation of the Blind (NFB). In addition to the topographical models, we have developed models of other data sets that have a significant Goddard role in their creation. We have translated Hubble images into 3-dimensional data and created models based on them, as we have also done for space plasma physics data.

Planned Future Work:

We have partnered with the Smithsonian’s Air and Space Museum to introduce the use of these models in a museum environment. We are also searching for ways to make Earth models more engaging and realistic, for Earth features are not as dramatic as those on Mars. Attempts to highlight Earth terrain features by altering the vertical scale has led to unrealistic modeling, but several possibilities exist to address this problem.

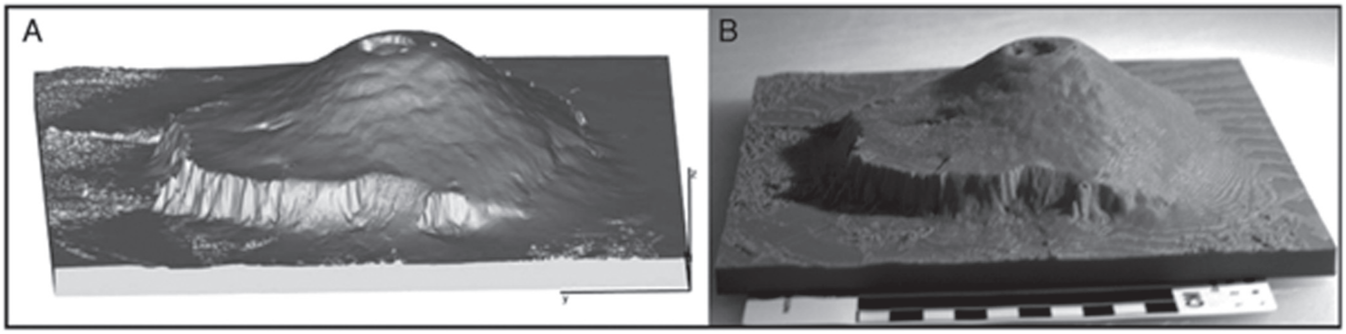


Figure 1. (a) Computer graphic image of Olympus Mons topography; (b) Photograph of the extruded plastic model produced from the image. For both cases, the vertical scale was exaggerated by a factor of 7 to better show topographic details.

Summary:

Our project provides a novel tactile dimension to remote surveying data in the creation of three-dimensional models of planetary surfaces. These are engaging to the public, serve as educational tools for school children, and provide visually impaired people with exciting access to the world of planetary science. From an outreach perspective, the use of data acquired through Goddard's Mars Orbiter Laser Altimeter instrument raises awareness of Goddard's mission and inspires the public with images and facts about Mars. Our criterion for success is to transfer this technology to an appropriate science education organization to be used as an educational tool. A significant obstacle that we have encountered is the limitation of the vertical resolution of the rapid prototyper, the machine "printing" the three-dimensional model. Vertical resolution refers to altitude, the topological features of the land. Compared to Mars, the Earth is flat. Thus, our Earth models are not as engaging or realistic as the Mars models. When we increase the vertical stretch by a factor of 10 to bring out features on Earth, mountains look like spikes. This obscures real features and makes interpretation of the models difficult. Fixes include refining the scale -- where one inch equals 100 miles instead of 1,000 miles, for example -- creating larger models, and using higher-resolution rapid prototypers. We are exploring these possibilities.

Balloon Student Experiment Carrier

Principal Investigator: Keith Koehler (Code 130)

Co-Investigators: David Gregory (820), Robby Ester (820)

Initiation Year: 2003

FY 2003 Authorized Funding: $25,000

Actual or Expected Expenditure of FY 2003 Funding: PSL, $25,000

Status of Investigation at End of FY 2003: Transition to other funding

Expected Completion Date: Summer 2005

Purpose of Investigation:

The purpose of our project is to develop an experiment carrier for dedicated scientific student balloon missions. The experiments may be active or passive, designed by students in kindergarten through university level. The carrier bus will incorporate common systems such as mechanical interface, power, data acquisition, and telemetry systems. Also, real-time camera pan and tilt capability will be provided along with real-time experiment commanding and data reception via the web. By our providing a common system with power and telemetry, students will be able to concentrate on developing their Earth and Space Science experiments. The carrier concept is designed to provide ten student experiment modules. Each 3.4-cubic-foot module can accommodate a 15-pound experiment. The experiment process from design to launch can be one year. Flights are to be conducted from the National Scientific Balloon Facility (NSBF) in Palestine, Texas. The flights are expected to be about six hours at around 100,000 feet altitude.

Accomplishments to Date:

The project has not progressed as planned. Initial flight was targeted for the summer 2004 but has now been delayed. Because flights from the NSBF are limited to the summer, the delay is one year. The project received notice of the DDF award in late March 2003. Changes in the Balloon Programs Office and team member workload and assignments during the summer precluded work on the project. In early December 2003 project planning was resurrected. The DDF of $25,000 has been targeted to be spent on common balloon system components that are compatible with NSBF systems, such as transmitters.

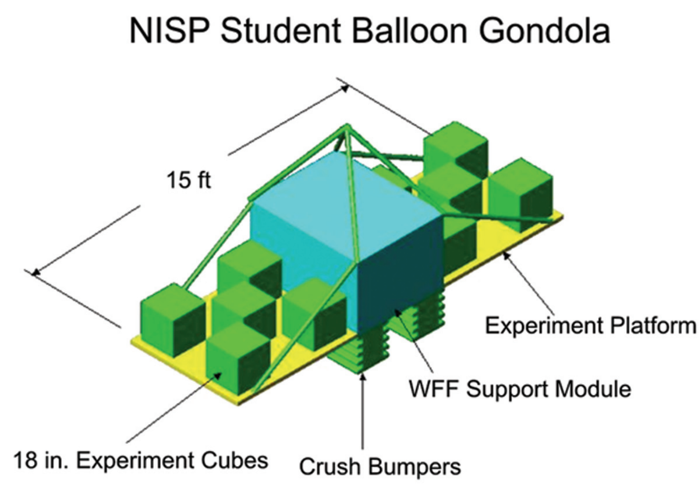


Figure 1. NISP student balloon gondola

Planned Future Work:

In FY 2004 our project will begin design and construction of the experiment gondola system and design of the telemetry and electronic systems. A FY 2004 DDF award has been announced for a student ground network development project. The system has applications for student balloon flights and will be incorporated into the program. A test flight of the balloon system is planned for summer 2005.

Summary:

The student experiment carrier will use common mechanical and electrical interfaces for each experiment. Use of the web will allow students to control and monitor experiments from anywhere in the United States. The carrier will allow thousands of students to fly experiments to the edge of space.

As a component of NASA Student Flight Projects effort, students through the university level will get hands-on experience in designing, building and flying experiments and analyzing their data. Such educational and public outreach offers valuable visibility for NASA. One success criterion is a first successful mission; others will be program sustainability, educational effectiveness and growth. Staff availability to work on the carrier has been the major hurdle, as has securing full funding for the project.

Handheld Mars Exploration

Principal Investigator: David Matusow (Code 588)

Co-Investigators: Joe Sparmo (585)

Initiation Year: 2001

Aggregate Amount of Funding Authorized in Earlier Years: $15,000

FY 2003 Authorized Funding: $4,500

Actual or Expected Expenditure of FY 2003 Funding: $4,500

Status of Investigation at End of FY 2003: Completed competition with the Odyssey School; look to change architecture to host more schools in future years

Expected Completion Date: completed

Purpose of Investigation:

The goal of this investigation was to build upon previous Handheld Mars Exploration (HAMEX) efforts to infuse PDA technology in the classroom for real-time science education. Essentially we enable students to use real data, miniature rovers and models of the Martian landscape to think through an exploration much like NASA scientists and engineers do. The students must explore the surface of Mars with a fixed amount of fuel and time.

Figure 1. A view of the Mars terrain located at the GSFC visitor's center.

Accomplishments to Date:

A Mars simulation environment was set up at the GSFC visitor's center, where two different classes from the Odyssey School in Baltimore held a competition. Students, using their personal digital assistants (PDAs), planned and controlled simulated rovers (using Lego Mindstorm robots) to try and achieve a variety of scientific goals including rock studies and searches for signs of water. These teams used their PDAs to not only predict and compute the rovers planned movements across the simulated Mars terrain, but they also used them to obtain real-time information on their rover and the "science" mission it was involved with. This highly successful activity was detailed at a talk given at the MICCA (Maryland's main technology in Education conference) in Baltimore.

Planned Future Work:

Based upon the work already completed, the HAMEX team hopes to create a new Mars environment at the visitors center that will allow many different schools to come and compete in an ongoing Mars competition. Working with the visitors center staff, schools will prepare ahead of time to come to Goddard and compete using rovers on the simulated Mars-scape. This will closely resemble the MERS missions currently en-route to Mars.

Summary:

This project is unique in its use of state-of-the-art technology (PDAs) to help teach science in the classroom using real-time space data. Furthermore, it takes advantage of the excitement of space exploration to motivate and educate students and hopefully spark the next generation of scientists and engineers. Goddard benefits from this not only though great publicity, but, by doing the research, we are gaining new insights into the use of PDAs for science data missions (planning and data access). This activity was highly successful in that the competition was successfully run, and the students really enjoyed the activity. Post activity analysis by the school indicates a high degree of enjoyment by the students, and a lot of material was absorbed in the different areas of science, math and engineering.

Figure 3. Odyssey School students working on the HAMEX project.

Figure 2. PDA screen captures showing rover planning and data retrieval tools.

A Practical Application of Ocean Color Methodology to an Undergraduate Curriculum

Principal Investigator: Tiffany A. Moisan (Code 972, WWF)

Co-Investigators: Brian A. Campbell (SAIC), Matt Linkswiler (EG&G), Robert W. Swift (EG&G), Jim Yungel (EG&G), Madhumi Mitra (University of Maryland Eastern Shore), Julie Ambler (Millersville University)

Initiation Year: 2002

Aggregate Amount of Funding Authorized in Earlier Years: $13,000

FY 2003 Authorized Funding: $50,000

Actual or Expected Expenditure of FY 2003 Funding: In-house labor and equipment, $35,000; Marine Science Consortium, $5,000

Status of Investigation at End of FY 2003: To be continued in FY 2004 with funds remaining from FY 2003

Expected Completion Date: 2004

Purpose of Investigation:

We have developed phytoplankton ecology class material and investigated the potential of a low-cost spectroradiometer for education and research by undergraduate students. A spectroradiometer is a device to analyze light -- in this case, light reflected from phytoplankton. Phytoplankton play a critical role in regulating global CO_2 and climate, yet the public has little or no understanding of the importance of the microscopic marine algae or how phytoplankton abundance and productivity can be monitored at global scales. On the undergraduate level, phytoplankton ecology is often taught in a classical manner where freshwater phytoplankton are examined under microscopes and classified taxonomically into different groups. Thus, there is a critical need for updating oceanographic education at the undergraduate level to modern ways of estimating phytoplankton concentration in the global ocean. New techniques to study phytoplankton dynamics have been developed in the past decades, in particular with the introduction of satellite remote sensing of ocean color. The "hands-on" approach developed in this project facilitates understanding spectral absorption and scattering. These form the basis for satellite retrieval of phytoplankton abundance from ocean color radiance imagery. Use of the spectroradiometer from docks and shipboard is augmented by ocean color satellite imagery from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer (MODIS) projects. With these systems, students sample these satellites' aerial coverage, "calibrate" the satellites, and derive chlorophyll estimates (e.g. ocean color).

Accomplishments to Date:

Undergraduate students attended classes led by Tiffany Moisan at the Wallops Flight Facility and Madhumi Mitra at the University of Maryland Eastern Shore. These focused on optical, biological, and engineering applications of ocean color methodologies. Students then applied the classroom to the shipboard research. Research cruises aboard the R.V. Phillip N. Parker (figure 1) were conducted with Marine Science Consortium and University of Maryland Eastern Shore undergraduate students. These cruises allowed for hands-on research, including filtering for phytoplankton (figure 2), use of a hand-held spectroradiometer, ocean trawling, and a Conductivity-Temperature-Depth Profiler (CTD). This data was then analyzed at the respective institutions.

A "Foundations of Phytoplankton" website has also been developed to assist students with phytoplankton research and information, including particular areas of research pertaining to ocean color methodologies. The website particularly emphasizes basic knowledge to the public, has been utilized at the high school and undergraduate level, and serves as a public outreach tool as well. The equipment and data has been instilled into the Marine Science Consortium curriculum, which sponsors undergraduates from 13 universities. We presented this data at the Operational Water Quality Remote Sensing Meeting in Charleston, South Carolina, in October 2003.

Figure 1. Students, instructors, and NASA personnel aboard the R.V. Phillip N. Parker

Figure 2. University of Maryland Eastern Shore student filtering for phytoplankton

Planned Future Work:

It is planned that this work will continue under other funds. Several potential sources have been sought out, including those at UMES and other funding agencies. We have plans to submit a proposal to NASA HQ in the upcoming fiscal year. Madhumi Mitra plans to write a publication utilizing data from her class that was collected in the Mid-Atlantic Bight, and a paper will be presented at an educational meeting in the summer of 2004.

Summary:

This project has been highly innovative because it not only combines the scientific attributes of utilizing a small low-cost handheld ocean color spectroradiometer designed by NASA/EG&G engineers, but it also offers students experiential learning experience in the Mid-Atlantic Bight on a small coastal research vessel. This program puts Goddard and WFF at the forefront of phytoplankton educational research interests for the purpose of enhancing undergraduate education and curriculum. Through the collaboration among NASA, the Marine Science Consortium, University of Maryland Eastern Shore (UMES) and Millersville University (MU), students have actually propelled themselves into a real-world NASA scientific research setting that has impacted their lives and may very well provide a foundation for the molding of future NASA scientists. The criteria for the success of this project are that the students successfully complete the shipboard scientific research and directly correlate this to the classroom lessons at UMES and MU. The applications of this student research transcend many scientific boundaries, including the study of optics, biology, and engineering. One risk factor that may have been an issue, but was not, was the possibility of not being able to successfully complete the research onboard the research vessel due to weather or marine constraints. This project may become a major effort for NASA in the near future.

FIRST Robotics Arena and Education Robot

Principal Investigator: Michael Wade (Code 547)

Co-Investigators: none

Initiation Year: 2003

FY 2003 Authorized Funding: $9,000

Actual or Expected Expenditure of FY 2003 Funding: In-house, $9,000

Status of Investigation at End of FY 2003: completed

Expected Completion Date: completed

Purpose of Investigation:

This DDF was for the purchase of upgrades to the Goddard Arena for the FIRST Robotics arena. The FIRST (For Inspiration and Recognition of Science and Technology) Robotics Competition is a highly regarded national engineering contest that immerses high school students (grades 9-12) in the exciting world of engineering. Teaming up with engineers from NASA, businesses and universities, students get a hands-on, inside look at the engineering profession. In six intense weeks, students and engineers work together to brainstorm, design, construct and test their "champion robot." The teams then compete in a spirited, no-holds-barred tournament complete with referees, cheerleaders and time clocks. The result is a fun, exciting and stimulating environment in which all participants discover the important connection between classroom lessons and real-world applications.

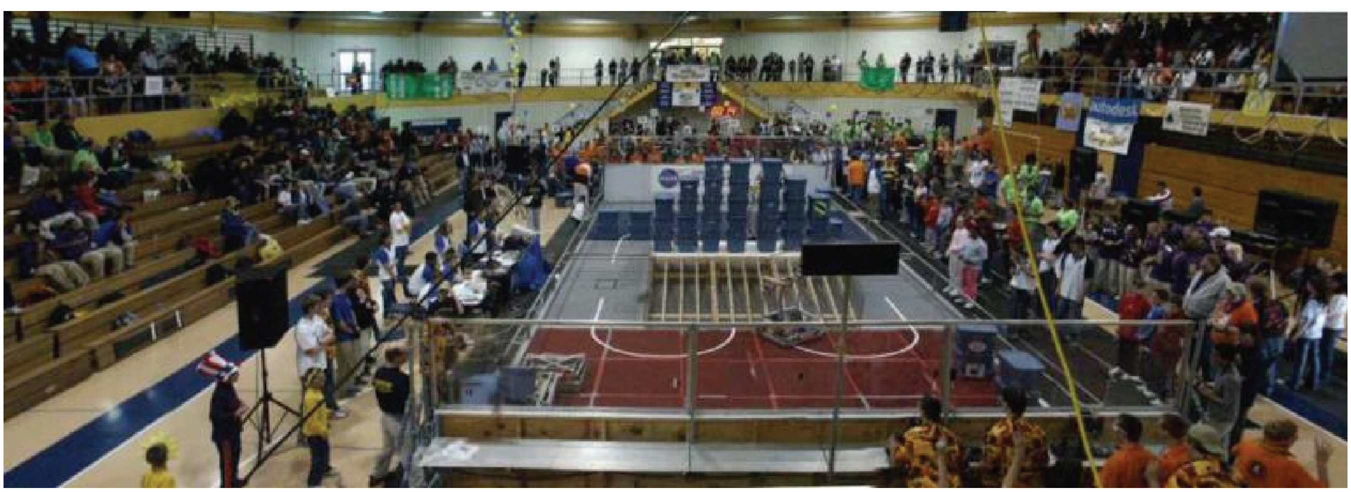
Accomplishments to Date:

I purchased and constructed a new floor for the arena. I also purchased electrical test equipment to run the events. The flooring consists of PVC Foam Sheets cut into 4ft-by-4ft squares. These panels have carpet glued to one side and Velcro placed on the other side. When assembled, the panels have Velcro holding them together and form an arena that is 24 feet wide and 54 feet long. The panels lend themselves equally well for assembly on a gym floor of a parking lot. The panels provide protection to the floor underneath and give a uniform playing surface for the robots. With the help of this DDF, over 3,000 students got to experience FIRST in six off-season events. The teams use the off-season events as a tool to get new students involved if FIRST and to get their students working together as a team, giving them a jump on the 2004 competition.

Scences from the FIRST Robotic Competition

Summary:

The FIRST program is starting its 12th year and has grown to include over 900 active teams. NASA is one of the major sponsors of this event. In 2002 NASA sponsored over 200 teams nationwide. Goddard sponsored 31 teams. NASA also sponsors regional competitions across the country. In March 2003 NASA and Goddard hosted a regional competition at the US Naval Academy. This has provided great visibility for NASA and Goddard in the media and in the community. The reason NASA is so heavily involved is that we are trying to motivate students to enter into engineering and technology related fields. The modest goal with FIRST is to "change the culture" by getting young people excited about and involved in science and technology. While young people show great enthusiasm for sports figures, they have little interest in the engineers and scientists who really make this country -- and our world -- great. Although such a concept is hard to quantify, our success criterion is to have raised awareness of the importance of engineering and science and the people who are leaders in this field. Lack of personal experience with inspiring young individuals is the problem. By partnering students and engineers, FIRST helps to motivate students to pursue carriers in science and technology.



Scences from the FIRST Robotic Competition

Archiving of Web Information at GSFC

Principal Investigator: Janet Ormes (292), Walt Truszkowski (588)

Co-Investigators: Gail Hodge (IIa), Nikkia Anderso (intern), Carmen Roscoe (intern), Clay Templeton (co-op), Daniel Smith, Jr. (IIa), Robert Allen and Alessandro Senserini (University of Maryland), Sidney Bailin (Knowledge Evolution, Inc.)

Initiation Year: 2003

FY 2003 Authorized Funding: $20,000

Actual or Expected Expenditure of FY 2003 Funding: $10,000 for Knowledge Evolution, Inc.; $10,000 for IIa

Status of Investigation at End of FY 2003: Request for follow-on DDF funding submitted for continuation in FY 2004

Expected Completion Date: August 2004

Purpose of Investigation:

The Goddard web is increasingly important as a source of scientific and technical information as Goddard researchers and engineers are disseminating information about projects and the results of their work via the medium. The purpose of this project is to develop and to prototype new technologies for capturing, organizing, preserving and accessing Goddard web-based knowledge assets in a context-sensitive way, with particular emphasis on dynamic web content (pages that are generated "on the fly" using executed programs) and the deep web (the portion of the web that lies behind database management systems). Due to the limited time and money made available under the DDF 2003, the scope of the project was reduced to include only the initial capture of web pages and the identification of an initial taxonomy of problems related to web capturing.

Accomplishments to Date:

We developed a protocol for capturing web sites (figure 1). Over 230 web sites (pages that form a cohesive intellectual unit) with over 89,000 web pages were captured. The captured content is stored and assigned a URL. The Goddard Core Metadata Element set, developed by the Library with earlier CIO funding, was tested against these sites and modified substantially to better describe Goddard web sites with regard to project-related information. Provision was made for assigning multiple taxonomies to the same object, so that the system could meet the needs of multiple audiences. (The prototype includes both the NASA-Wide Taxonomy under development by the Jet Propulsion Laboratory and the Earth Observing System Taxonomy proposed for its lessons learned prototype system.) Metadata records are created through automatic protocols for populating the elements supplemented by manual editing.

In order to make the result of the web capture more useful, a central metadata repository was developed that includes web sites, videos (streaming media for web casts of colloquia), images and documents. Open Archive Initiative (OAI) techniques were implemented to submit or harvest Goddard Core Metadata from these diverse digital object repositories. A Cross-Object Searching interface was developed to search the central repository and then display the object from its native system.

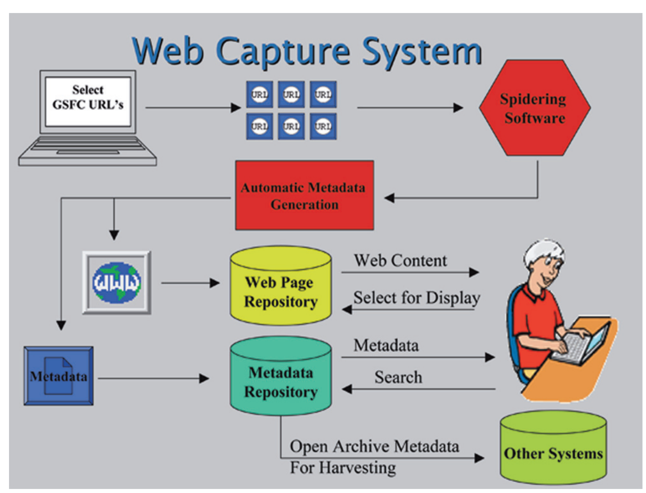


Figure 1. Web Capture System

A taxonomy of four web capture problems was identified for further investigation. The unstructured, fluid nature of

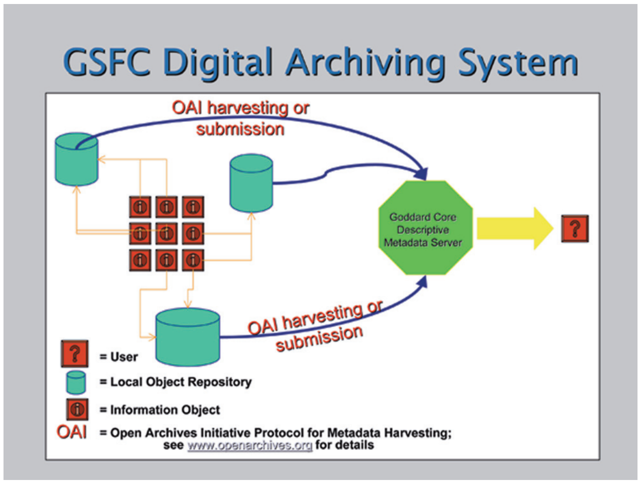


Figure 2. Creation of Central Metadata Repository for Multiple Digital Object Types.

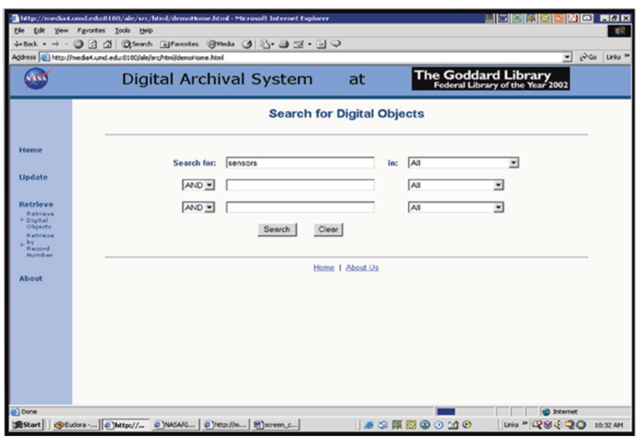


Figure 3. Digital Archiving System with Cross-Object Searching.

web authoring results in several secondary problems including the inability to reliably identify and locate web objects over time (resulting in "404 Not Found" errors); duplicates including the same objects appearing in multiple locations or in multiple formats; and changes to the content of objects over time without versioning. In addition, the spidering tools tested in this project proved inadequate to capture Goddard's increasingly complex web sites. In particular, the tools did not preserve the directory hierarchy of linked web pages causing links in the archived pages to fail. Dynamic web pages that are generated "on the fly" could not be captured. Dynamism results from programs executed either by the web server, such as Java Server Pages (JSP), Cold Fusion pages (CFM) or Active Server Pages (ASP), or contained within the web page itself and executed by the web browser (usually JavaScript). The latter can be further classified as flyovers (images that change when the mouse is placed on the image); regularly updated pages, such as daily satellite images; and embedded feeds in which a web page acts as a window into another web site providing dynamic information. Finally, the deep web, that portion of the web that lies behind database management systems and other non-transparent web-based programs, cannot be accessed because of access controls or because of the need to understand the underlying search engine that can expose the contents of the database. Gail Hodge organized a special session at the Dublin Core 2003 Conference in Seattle on September 30, 2003, on project metadata. Dr. Robert Allen and Clay Templeton presented a paper on the Goddard Core as an example of metadata for projects. Over 50 people, including representatives from The Boeing Company, attended the session. The work has also been presented to other agencies that have an interest in project metadata, including the National Agricultural Library, the National Archives and Records Administration, the Jet Propulsion Laboratory, and the National Institutes of Health/National Library of Medicine. The Web Capture System received a positive review by the Library Visiting Committee in May and when it was demonstrated at the Library's Open House in October. The Cross-Object Searching was enthusiastically received when it was presented to the Library Council and to the Knowledge Management Team. Papers are being prepared on the Digital Archiving System (D-Lib Magazine) and on the Goddard Core (Science and Technology Libraries) for publication in 2004.

Planned Future Work:

Based upon these exciting 2003 DDF results, the next phase of the research will focus on further developing the taxonomy of web capture problems and identifying ways to automatically categorize the problems and initiate appropriate programmatic solutions that result in improved capture of the pages. Work will continue to more effectively create metadata automatically based on the content and context of the captured sites. The team will investigate how to preserve these types of web content, with an analysis of the factors that influence the balance between preservation and the ability to render the object in the future. Plans are underway to use the web capture system to capture and preserve web sites related to the Hitchhiker Project which will be going into hibernation at the end of this year. In addition, plans are underway to incorporate different types of objects into the cross-search system, including project documents.

Summary:

The project captures web sites that are key knowledge assets for the Goddard community. This project (1) developed innovative techniques for enhancing the metadata extraction, (2) modified the Goddard Core Metadata Scheme to better describe project-related information, and (3) enumerated an initial taxonomy for web capture problems. The Goddard Core provides a metadata framework and core set of elements that could be used across the Center and across NASA to describe project information. The techniques for web site capture can support Goddard's knowledge sharing, lessons learned and e-records initiatives. Complete success would have occurred if all aspects of the Goddard web sites had been captured. However, because the Goddard web sites are extremely complex, complete success was not achieved. The complexity of web site design is exceeding the capabilities of the tools available. Rather than one-off solutions for each web development technology, the planned Phase II will identify factors that can solve web capture problems independent of the web development technology that is used. It will also begin to identify how these solutions impact long-term preservation and reuse of these web sites.

NASA GSFC Center Director's Discretionary Fund: Distribution Resources for FY 2003

Project Title and Investigator	Initiation Year	Partnership in Academia	Funding Authorized in FY'02 (in thousands of $)	Total FY'03 Funding Authorized (in thousands of $)	Project Status	Expected Completion Date (year)
Engineering/Technology						
Development of a Martian Dust Characterization Instrument *Brent Bos*	2003	√		13	Open	Aug. 2004
High Accuracy, Cryogenic, Infrared Refractometer *Bradley Frey*	2003			52	Open	2004
Oriented Carbon Nanotube Composites Extrusion *Dan Powell*	2003			56.5	Open	Oct. 2004
Cryogenic Large Angle Flexures (LAF) *Claef Hakun*	2003			20	Open	Apr. 2004
Magnetic Optical Wheel Solenoid (MOWS) *James Marsh*	2003			59	Open	Feb. 2004
Hyperspectral Sensor for Image-Based Wavefront Sensing *Bruce Dean*	2003			26	Closed	Dec. 2003
Tomographic Processing for Image-Based Wavefront Sensing *Bruce Dean*	2003			4.5	Closed	2003
An Interferometer for Low Uncertainty Vector Metrology *Ronald Toland*	2003			40	Open	Feb. 2004
Cooling Large Telescopes and Instruments to 4K Using Adiabatic Demagnetization Refrigerators *Michael DiPirro*	2003			70	Open	Dec. 2004
Expitaxial Silicon for Cryogenic Bolometers *Christine Allen*	2003			50	Open	Aug. 2004
Cryogenic Polarization Chopper for Millimeter and Sub-mm Waves *James Chervenak*	2003			50	Open	Mar. 2004

Project Title and Investigator	Initiation Year	Partnership in Academia	Funding Authorized in FY'02 (in thousands of $)	Total FY'03 Funding Authorized (in thousands of $)	Project Status	Expected Completion Date (year)
RF MEMS Switches *Eric Simon*	2002		60	40	Closed	2003
Ultra High-Density Printed Circuit Boards (PCB) with Embedded Passive Devices *Harry Shaw*	2003			35	Open	Dec. 2004
Formation Control Experiments Inside the Space Station *Russell Carpenter*	2002	√	35	30	Open	2005
A Colloidal MEMS Thruster *Eric Cardiff*	2003			25	Open	Dec. 2004
Catalyst / Substrate Materials for HAN Decomposition *Mark Underdown*	2003			24	Open	Jun-04
Space Science						
Development of Environmental Control Systems for Integration and Test of LISA *Jordan Camp*	2003			95	Open	Nov. 2004
Thick-Format Dichroic Mirror *Alan Kogut*	2003			65	Open	Sept. 2004
Active matrix pixel proportional counter for X-ray polarimetery *Rob Petre*	2003			65	Closed	2003
Design and Test of an Innovative Calorimeter for the Study of High-Energy Cosmic Rays *John Mitchell*	2003			62	Open	Nov. 2004
Thin film stacks for enhanced X-ray reflection in the 1-4 keV range *Scott Owens*	2003			55	Open	2004
Miniature Stackable Mass Spectrometer Cavities of Permanent Magnet Films *Fred Herrero*	2003			63	Open	Oct. 2004
Flux Transformers for Magnetic Calorimeter X-ray Detector Arrays *Thomas Stevenson*	2003	√		50	Open	Aug. 2004

Project Title and Investigator	Initiation Year	Partnership in Academia	Funding Authorized in FY'02 (in thousands of $)	Total FY'03 Funding Authorized (in thousands of $)	Project Status	Expected Completion Date (year)
Fluorescent Probes for the Identification of Extra-Terrestrial Amino Acids *Harry Shaw*	2003			50	Open	Dec. 2004
Development of "Mushroom" Absorbers for Magnetic Calorimeter X-ray Detector Arrays *Frederick Porter*	2003			50	Open	Aug. 2004
High Precision Mirror Reflectance Uniformity for Coronagraphy *Charles Bowers*	2003			60	Open	Apr. 2004
Characterization of MEMS Deformable Mirrors (DMs) *Sara Heap*	2003			47	Open	Apr. 2004
Single Electron Transistors as Multiplexers for Large Format Semiconducting Bolometer Arrays *Harvey Moseley*	2003			39	Open	Sept. 2004
Dual-Polarization Millimeter-Wave Planar Detector Array *Ed Wollack*	2003			70	Open	2004
Spectral Contrast Enhancement Techniques for the TPF Focal Plane *Drake Deming*	2003	√		80	Open	Aug. 2004
Earth Sciences						
New Lidar Technique for Measuring the Direct and Indirect Effect of Aerosols - FY2003 Extension *David Whiteman*	2002	√	50	50	Open	Sept. 2006
A Spectral-Ratio Biospheric Lidar *Jonathan Rall*	2003			25	Closed	2003
High rep rate laser transmitter for high efficiency, high accuracy planetary surface mapping. *D. Barry Coyle*	2003			45	Open	2005
Multi-Tuned Active/Passive Antenna Element Characterization *Larry Hilliard*	2003			17	Open	Aug. 2004

Project Title and Investigator	Initiation Year	Partnership in Academia	Funding Authorized in FY'02 (in thousands of $)	Total FY'03 Funding Authorized (in thousands of $)	Project Status	Expected Completion Date (year)
Analysis of in situ and remote sensing aerosol absorption data - Extension *Yoram Kaufman*	2002	√	60	25	Closed	2003
In-Situ Combination of Magnetic and Satellite Image Data *Compton Tucker*	2003	√		10.6	Closed	2003
Investigation of Bose-Einstein Condensates for Advanced Gravity Gradiometer Designs *David Skillman*	2003			47	Open	Jun. 2004
Optical Measurements of Particulate Organic Carbon in the Sea *Michael Behrenfeld*	2003			65.5	Open	Dec. 2004
Optical Properties of Black Carbon and Terrigenous Chromophoric Dissolved Organic Matter in the Coastal Ocean *Antonio Mannino*	2003			71	Open	2004
Global Carbon Cycle: Development of a Bicarbonate Ion Lidar *Frank Hoge*	2002		76	52	Open	Dec. 2003
A Miniaturized Eddy Covariance Instrument for small UAVs *Paul Houser*	2002		30	30	Open	Sept. 2004
Modeling Urban Land-Atmosphere Interactions *Christa Peters-Lidard*	2003	√		50	Open	Mar. 2004
Frozen Hydrometeor and Snowfall Inference from Millimeter-wave Radiometry *Gail Jackson*	2003	√		36	Open	2006
Education and Outreach						
Remote Sensing at Its Best: A Model Plan to Share UAV Technologies with Educational Communities *Patrick Coronado*	2003	√		25	Open	Dec. 2004
Exploratory Collaborative Study: Innovative Approach to Mathematics Education *Garcia Blount*	2003	√		10	Open	Dec. 2004

Project Title and Investigator	Initiation Year	Partnership in Academia	Funding Authorized in FY'02 (in thousands of $)	Total FY'03 Funding Authorized (in thousands of $)	Project Status	Expected Completion Date (year)
Student Experimenters Virtually Experiencing NASA *Chuck Brodell*	2003	√		20	Open	Mar. 2004
GSFC/UMES Education Outreach for Ocean Exploring at Wallops Flight Facility *Russell Dufrene*	2003	√		25	Open	Oct. 2004
Student Aerosol Measurements for the Baltimore Asthma Project *Brent Holben*	2002	√	25	35	Closed	2003
The Pavilion; Collaboration between Art and Technology *Joseph Howard*	2003	√		4.5	Open	May-04
Mathematics, Engineering and Science Enrichment Program *Lisa Johnson*	2002	√	20	16.5	Open	Dec. 2004
Exploring Planetary Topography in the Classroom Using 3-Dimensional Models *John Keller*	2003	√		19	Open	Dec. 2004
Balloon Student Experiment Carrier *Keith Koehler*	2003	√		25	Open	2005
HAMEX Mars Exploration *David Matusow*	2002	√	5	4.5	Closed	Sept. 2003
A Practical Application of Ocean Color Methodology to an Undergraduate Curriculum *Tiffany Moisan*	2002	√	13	50	Open	2004
FIRST Robotics Arena and Education Robot *Michael Wade*	2003	√		9	Closed	Jul. 2003
Water Cycle and Hydrology K-12 Education and Public Outreach *David Toll*	2003	√		5	Closed	Sept. 2003
Archiving of Web Information at NASA and GSFC *Janet Ormes*	2003	√		20	Open	Aug. 2004
Programmatic & Student Internship Support				**161.4**		
Total Allocation of FY 2002 GSFC DDF SUPPORT				**2400**		

Report Preparation

Adrienne Byrd, coordination
Richard Fahey, coordination
Chris Gunn, cover design/many photos
Irene Stone, layout
Pat Tyler, layout
Christopher Wanjek, editing

National Aeronautics and Space Administratin
Goddard Space Flight Center